INVESTIGATION INTO THE VIABILITY OF USING PERVIOUS PAVEMENTS IN STORM WATER MANAGEMENT TO REDUCE FLOODING IN TOWNSHIPS

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DECLARATION

I hereby declare that the dissertation submitted for the degree Master of Engineering - Civil, at the University of Johannesburg is my own original work and has not been previously submitted to any institution of higher education. I further declare that all sources cited or quoted are indicated and acknowledged by means of a comprehensive list of references.

Arthur Kazoka

DEDICATION

This study is dedicated to my family. Through their love and support, it was possible for me to complete the study. To the Almighty God who is the pillar of my life, I thank you.

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The completion of this interesting study was made possible with the help of many people to whom I wish to express my sincere gratitude.

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ABSTRACT

South Africa like many other countries worldwide has been facing a growing problem of urbanization; increasing the population living in urban areas. One immediate implication is the need for increase in impervious pavements/surfaces being built to have good un-interrupted road transport network among other things. Traditionally, the roads are designed and constructed with impervious material to withstand untimely failure due to fatigue and extreme weather conditions. However, these impervious surfaced pavements cause damages to the environment through storm water runoff which cause peak flow flooding. This is because their surfaces are constructed to be water tight to prevent ingress of water into the road pavement structure. This practice is not environmentally sustainable, causes heat island effect and causes peak flow flooding which is detrimental to the municipal infrastructure and human life. To prevent these detrimental effects, there is a need to use more environmentally friendly and sustainable pavements/surfaces which are pervious in nature.

The aim of this study was to address the above challenge through scientific investigation of the suitability of pervious pavements in storm water management to reduce peak flow flooding in townships. The investigation was to establish what type of pervious pavement is more suitable for township development to effectively reduce storm water runoff and peak flow flooding. Three types of pervious pavements were investigated namely, Interlocking pavers, concrete and asphalt. Diepsloot Township which is situated in the Western Region of Johannesburg was used as the study area.

Field research to determine critical factors in pervious pavement installation were conducted. The critical factors researched in this study are; topography/terrain of the area, existing street sizes, houses proximity to the streets, available open space & land use and contamination potentials of storm water run-off. After the field research had been completed, a total of 30 streets randomly selected were measured. Laboratory experiments were conducted to determine the filtration rates of each of the three pervious pavement samples collected from commercial suppliers. A total of 16 replicate filtration rate laboratory experiments using clean water for each pervious pavement sample were conducted under same laboratory conditions. Furthermore, clogging tests for each pervious pavement sample was conducted using sand and silt contaminated water. A total of 12 replicate tests were conducted.

The laboratory test results obtained for each type of pervious pavement sample were compared in order to determine the most effective pervious pavement in terms of filtration rate with clean water and contaminated water (clogging test). The infiltration rate results using clean water indicate that pervious asphalt was most effective with an average infiltration rate of 0.282 *l/s* followed by pervious interlocking pavers with 0.265 *l/s*. Pervious concrete was last with 0.145 *l/s*. The clogging test results indicate that pervious asphalt still was more effective. It recorded less infiltration rate reduction having reduced by 17.38% followed by pervious interlocking pavers having reduced by 36.73%. Pervious concrete was the worst with 45.52% reduction in infiltration rate.

In order to establish which pervious pavement type was more suitable for township development to mitigate peak flow flooding and social economic challenges experienced, field research results were taken into account. Asphalt was favourable in terms of infiltration rate while interlocking pavers were favourable in terms of addressing some of social economic challenges of the township communities such as un-employment. It was concluded that interlocking pavers are more suitable in this regard to address peak flow flooding and social economic challenges in township development.

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LIST OF ABBREVIATIONS

AS	Asphalt
ACRP	Airport Cooperation Research Program
ID	Internal Diameter
IDP	Integrated Development Plan
IUDF	Integrated Urban Development Framework
CoGTA	Cooperative Governance and Traditional Affairs
l/s	Litres per second
m^3	Cubic metre
SUDS	Sustainable Urban Drainage System
SAICE	South African Institution of Civil Engineering
PICP	Permeable Interlocking Concrete Pavements
UJ	University of Johannesburg

GLOSSARY

Asphalt surface (AS)	Paved with asphalt (Road surfaced with asphalt).
Check-dams	Depressions constructed across the slope to lower the flow velocity. They reduce the storm water runoff velocity.
Clogging	To reduce or obstruct filtration process with silt or sticky matter which drops the hydraulic performance of pervious pavements/surfaces over time.
Grid pavement systems	These are standard concrete blocks which have a large percentage of the surface area as open. The open area allows for water to penetrate into the sub-base. The pervious interlocking paving blocks are designed to have openings on the joints once laid to allow storm water to infiltrate.
Groundwater	Water occurring naturally below ground level or water pumped, diverted or released into a well for storage underground.
Heat Island Effect	Urban heat island occurs when an urban area or city (developed) experiences warmer temperatures higher than nearby rural areas (less developed). This happens when urban areas surfaces absorb more heat during the day and release it at night creating significant local temperature differences which can be felt especially at night than during the day, and it is most apparent when winds are weak. It is considered to be a form of local climate change as opposed to global climate change. The effects of this climate change are confined to a specific area(s) and can make significant impact to the local climate.
Infiltration rate	The speed or velocity at which water enters into and leave the soil/matter.
Impervious surface	Surface that repels rainwater and does not permit it to infiltrate through into the ground.
Oportunity cost	This represents the benefits foregone by one alternative, when choosing another alternative.

Partition berms	Platforms constructed across the slope to slow the storm water run-off velocity. Usually they are constructed using natural earth.
Pervious surface	Surface that allows the percolation of water into the underlying soil layer.
Pervious Portland Cement Concrete (PPCC)	Permeable concrete which consists of similar types of ingredients to conventional Portland Cement Concrete (PCC) but with no or small amount of fine aggregate and with open-graded coarse aggregate. It provides a porous medium to rapidly infiltrate storm water.
Peak flow flooding	The maximum discharge of storm water that can occur for the selected rainfall intensity from a specific basin and that, the discharge occurs for a specific time of concentration and beyond.
Porous asphalt	Permeable asphalt surface mostly placed over aggregate base layer (Reservoir course).
Reservoir course	The base pervious pavement base layer consisting of aggregate material.
Subsurface terracing	Earth platforms within the sub-base/base layer built along contour lines of slope to slow the flow of water. They are gradient Controls.
Surface flow run-off	Flow of water that occurs when excess storm water flows over the surface.
Urbanization	Migration of people from rural areas to urban.
Watershed areas	It is a land area that receives rainfall and channels the flow to creeks, streams, rivers, and eventually to outflow points such as reservoirs, bays, and the oceans. A Watershed can be small in size to large areas covering thousands of square kilometers.

CHAPTER 1: INTRODUCTION

1: INTRODUCTION

1.1 Background

Urban development, industrialisation and urban migration known as urbanisation, increase the use of impervious pavements (Zeng, *et al.,* 2019; Chopra, *et al.,* 2011). These impervious pavements are responsible for a significant portion of the nation's leading threat to surface water quality caused by non-point source pollution generated by storm water runoff (Kamali, *et al.,* 2017; Chopra *et al.,* 2011). These impervious surfaces replace natural grasslands including natural surfaces and they pose significant threat to the urban environment and its ecosystem (Qin, *et al.,* 2018; Miller and Hutchins, 2017). This is so because impervious surfaces prevent rain water from infiltrating into the ground instead it becomes storm water runoff and peak flow flooding carrying different types of pollutants into receiving water bodies (Zhu, *et al.*, 2018).

1.2 Storm water and its effects

Storm water is runoff from an area as a result of rainfall which is discharged to drainage infrastructure or natural water cause (Bruinsma, *et al.,* 2017; Chopra, *et al.,* 2011). Storm water carries various pollutants from different sources. Polluted storm water runoff discharges at different points with un-controlled quantities of pollutants which results in habitat loss in the receiving water body (Chopra, *et al.,* 2011). This renders storm water treatment un-effective, un-economical and un-sustainable since the exact quantities of storm water pollutants can't be predicted for all discharge points of every impervious surface (Miller and Hutchins, 2017; Preeti and Dwarakish, 2015). In addition to receiving water pollution, surface flow and peak flow flooding is increased causing damage to the environment, municipal infrastructure and pose danger to human safety (Rahn, *et al.,* 2017; Lindow, *et al.,* 2015). These adverse effects of surface runoff and peak flow flooding make impervious pavements environmentally un-sustainable (Miller and Hutchins, 2017).

For many decades, the main concern about storm water runoff from pavements has been drainage and safety, with emphasis on how to drain the water off the pavement surface as quickly and efficiently as possible (Preeti and Dwarakish, 2015). However, this practice is not environmentally sustainable (Preeti, *et al.,* 2015; Moghanddam, *et al.,* 2012). For many years, many designers and planners considered that once the storm water is taken off the pavement surface and discharged into the drainage system, the problem is solved (Chopra *et al.,* 2011). Unfortunately, this only solves part of the problem which is draining the storm water from the pavement. This does not solve the problem of environmental effects the storm water causes downstream (Chopra, *et al.,* 2011) this surface run off ends up somewhere downstream once it is drained from the pavement's surface, and typically causes negative impacts to the environment and receiving water bodies. This is so because traditional impervious pavements are designed to have sufficient cross slope and longitudinal slopes which increase the velocity of the storm water runoff directing it away from the pavement surface before ponding can occur (Chopra, *et al.,* 2011) Furthermore, (Chopra, *et al.,* 2011) states that, this causes erosion, channel widening, flooding, and spreading of pollutants downstream.

Although many impervious pavement designers strive to ensure that wearing courses of a pavement can be kept watertight with good surfacing (impervious) which is water tight, it is not always the case (Zhang, *et al.,* 2018; Yong, *et al.,* 2013). The inevitable stresses and pressures of traffic loading, temperature fluctuations, oxidation, weathering, and freeze thaw cycles are constantly working to open cracks that allow water to enter (Zhang, *et al.,* 2018; Yong, *et al.,* 2013; Sasalone, *et al.,* 2012; Chopra, *et al.,* 2011). The water that enters into the pavement system becomes trapped and unable to be expelled out quickly causing pore water pressures that result in piping and pumping that erode away sub-soils and damage the pavement structure (Yong, *et al.,* 2013). It also impacts on the structural integrity of the pavement structure because it becomes soft (Yong, *et al.,* 2013; Sasalone, *et al.,* 2012). The best practical way to prevent water from accumulating in the pavement structure is to drain it away from the full width of the pavement surface which then becomes costly (Yong, *et al.,* 2013; Chopra, *et al.,* 2011).

Every time there are floods; either Pluvial or Fluvial in nature, the urban ecosystems, infrastructure and lives are negatively affected (Miller & Hutchins, 2017; Elmqvist, *et al.,* 2015). These threats and challenges posed by flooding are experienced in both urban and densely populated areas (informal & formal settlements) around the world including South Africa. Research has proven that floods caused by impervious pavements/surfaces can be mitigated through applications of Sustainable Urban Drainage Systems (SUDS) in the form of pervious pavements (Kayhanian, *et al.,* 2019; Tixier, *et al.,* 2011). The pervious pavements/surfaces do not only prevent storm water runoff and peak flow flooding, they also preserve the urban ecosystems as well as overall improves health, aesthetics, social cohesion and overall well-being of the communities (Kamali, *et al.,* 2017; Elmqvist, *et al.,* 2015).

The problem of flooding is not lack of policy by the government of the day but the ever increasing impervious pavements/surfaces in these areas (Zhu, *et al.*, 2018; Miller and Hutchins, 2017). The South Africa Government through the Green Paper on Environmental Policy (1996) acknowledges that urbanisation creates environmental and social challenges which must be addressed. This can be achieved through integrated and holistic approach to environmental management to improve the quality of life of all citizens, particularly previously disadvantaged groups through sustainable use of the environment and its' protection for present and future generations. As the city's population grow, informal and formal settlements increase and more infrastructure such as housing, roads, electricity, water and sanitation needs due to the community increase.

In order to move towards government policy as stipulated in the Green Paper on Environmental Policy (1996) and overcome problems experienced due to impervious surfaces, there is a need to recognise the use of pervious pavements system as alternative management practice for sustainable storm water management (Kayhanian, *et al.,* 2019; Rahn, *et al.,* 2017). These types of surfaces are porous in nature and are alternative to the traditional impervious pavement surfaces and they provide a wide range of ecological advantages, environmentally friendly and they are often economically viable (Mersal, 2016; Elmqvist, *et al.,* 2015). They are also a solution to heat Island effect caused by impervious surfaces (Kayhanian, *et al.,* 2019; Rahn, *et al.,* 2017; Tixier, *et al.,* 2011).

To avoid problems caused by impervious surfaces which include high storm water runoff, peak flow flooding, surface water contamination and heat Island effect, there is a need to move towards more sustainable methods which involve the use of pervious pavements/surfaces (Zhu, *et al.*, 2018; Rahn, *et al.,* 2017; Kamali, *et al.,* 2017). In this research, the viability of using pervious pavements in storm water management to reduce flooding in townships is investigated.

1.3 Problem statement

In recent decades, South Africa like many other countries worldwide has been facing a growing problem of urbanization, i.e. increasing the population living in urban areas. To cope with this increasing urban population and economic growth demands, more pavements are being built to have good un-interrupted road transport network. Traditionally, the roads are designed and constructed with impervious surfaces to withstand traffic loading and stresses due to weather conditions. However, these impervious surfaced pavements cause damages to the environment through storm water runoff and peak flow flooding (Singh, *et al.,* 2018; Moghanddam, *et al.,* 2012). This is so because their surfaces are constructed to be water tight to prevent ingress of water into the road pavement structure. This practice is not environmentally sustainable, causes heat island effect (Qin, *et al.,* 2018) and it is detrimental to the municipal infrastructure and human life (Kayhanian, *et al.,* 2019; Singh, *et al.,* 2018; Rahn, *et al.,* 2017). To prevent these detrimental effects, there is a need to use more environmentally friendly and sustainable pavements which are pervious in nature (Mersal, 2016; Elmqvist, *et al.,* 2015).

The use of pervious pavements in place of impervious pavements in storm water management intensified in the last few decades (Cosic, *et al.,* 2015). The results show that pervious pavements can reduce storm water surface run off and peak floor flooding (Saadeh, *et al.,* 2019; Zhu *et al.*, 2018; Cosic, *et al.,* 2015). They are also environmentally sustainable with many environmental and ecological benefits over impervious pavements (Kamali, *et al.,* 2017; Mersal, 2016). However, other research suggests that pervious interlocking paving blocks and pervious concrete application still remains limited to parking lots, road side walks, pathways and light trafficked roads (Lindow, *et al.,* 2015; Razzaghmanesh, and Borst, 2019) due to some drawbacks inherited from their limited strength because of their porous nature and susceptibility to clogging (Zhong, *et al.,* 2018). However, these drawbacks may not hinder the use of these pervious pavements in townships since there are low traffic volumes in townships.

Further research into the strength of pervious interlocking paving blocks and pervious concrete pavements has established that, their structural compressive strength and durability under heavy traffic loading can be improved through the incorporation of supplementary cementitious material such as silica fume and fly ash (Saadeh, *et al.,* 2019; Zhong, *et al.,* 2018; Qin, *et al.,* 2018). Furthermore, clogging can be minimised or avoided through regular maintenance of the pavement surfaces (Sasalone *et al.,* 2012; Chopra, *et al.,* 2011). These research findings have attracted renewed interest in the last decade to further find ways as to how pervious concrete and asphalt pavements can be used to mitigate the effects of flooding in heavily traffic roads such as freeways (Jamshidi, *et al.,* 2019). However, there still exist knowledge gap on the use of pervious pavements in streets of densely populated areas in conjunction with other Sustainable Urban Drainage System (SUDS) such as detention ponds to alleviate the effects of storm water runoff and peak flooding including social economic challenges faced by the communities (Jamshidi, *et al.,* 2019). Once the pervious pavements are verified to be effective, the municipalities can adopt their use in townships in an integrated municipal infrastructure system to address environmental, social and un-employment challenges (Jamshidi, *et al.,* 2019; Kayhanian, *et al.,* 2019; Zhong, *et al.,* 2018).

Evidence of peak flow flooding is seen every year when South Africa's urban, formal and informal settlements are flooded and various municipal infrastructure and shelter are destroyed as well as loss of life in some cases. To mitigate these effects, there is a need to move away from impervious pavements towards pervious pavements (Xie, *et al.,* 2019; Mersal, 2016; Elmqvist, *et al.,* 2015). In this research, the viability of using pervious pavements into storm water management to reduce peak flow flooding in townships is investigated. Furthermore, due to lack of integrated storm water management and land use system, the research seeks to develop an integrated use of pervious pavements and land to manage storm water peak flow flooding in an environmentally sustainable manner and also address the communities' social economic challenges.

1.4 Objectives of the research

1.4.1 Broad Objective

The broad objective of this study was to investigate through field research and laboratory tests to establish which type of pervious pavement is more suitable for township development to effectively reduce storm water runoff and peak flow flooding. In order to achieve this, specific objectives were set using Diepsloot Township as study area.

1.4.2 Specific Objectives

In order to achieve the broad objective of the research, the following specific objectives were achieved. These are as follows:

1. To establish applicability of pervious pavements in South Africa townships as a mean of storm water management taking into account street width, length and availability of open spaces.
2. Conducted laboratory tests on three types of pervious pavements readily available in South Africa, with the view to establish the effectiveness of each type in storm water management through infiltration rates and clogging susceptibility.
3. To compare the three types of pervious pavements in terms of filtration rates and clogging susceptibility.
4. Establish best suitable pervious pavement system in a township based on the results obtained in specific objective 3 using field/local variables considered namely; existing local conditions of townships and shelters proximity to roads/streets.

1.5 Significance of the research

Migration of people to urban areas (Urbanisation) causes a significant increase in impervious surfaces, such as roads, driveways, parking bays and courtyards (Davis and Dougherty, 2017; Lindow, *et al.,* 2015). This results in increased storm water runoff, peak flow flooding and heat island effect (Zhu, *et al.*, 2018; Rahn, *et al.,* 2017; Lindow, *et al.,* 2015). The increase in storm water runoff, peak flow flooding and heat island effect have major adverse impacts on the water cycle, environment and the communities. Storm water runoff and peak flow flooding occur because impervious surfaces do not allow storm water to infiltrate through to the underlying layers. This result in increased surface runoff reduced flow inputs to groundwater systems and increased downstream pollution of water bodies affecting the aquatic life (Lindow, *et al.,* 2015; Furgason, 2006).

Various researches have proven that pervious pavements/surfaces can reduce storm water runoff, peak flow flooding and heat island effect (Xie*, et al.,* 2019; Rahn, *et al.,* 2017). Furthermore, they improve the quality of storm water entering the natural water resources and provide a wide range of social and ecological benefits (Rahn, *et al.,* 2017; Lindow, *et al.,* 2015).

Surface runoff and peak flooding is a major problem in urban and densely populated areas including those in South Africa townships that's why there is a need to find a sustainable solution to this problem. Hence this study which investigated the viability of using pervious pavements into storm water management to reduce flooding in townships was necessary. The findings will assist the municipalities to mitigate peak flooding in townships and its environmental effects. It will also address some of the social economic challenges township communities' experience.

1. 6 Study area

The study was conducted in Diepsloot Township (Figure1.1) . Diepsloot is a settlement in the western region of Johannesburg. It was established in

1995 initially as a temporally informal settlement/shelter for people who were evicted from informal settlements in Honeydew, Sevenfontein and Alexandra. In 1999, the area started to be formalised by the administrative Government then, by establishing a transitional council to register all people in the area so as to start with developments. Currently Diepsloot covers approximately 1014.681ha with about 138 329 people (Stats SA, 2011).

FIGURE 1.1: Study area locality map

(Source: http://www.streetmaps.co.za (2019))

Diepslot Township is is densely populated with houses close to each other and the streets. There is a stream/wetland stretching across the study area dividing it into two areas. The area terrain slopes towards the stream/wetland and the slope varies from flat and gentle rolling to steep rolling. The area received annual rainfall of 735mm in the year 2019 (South Africa weather service, 2019).

1.7 Structure of the dissertation

The dissertation is structured to have five chapters. The chapters are as follows:

i. **Chapter 1: Background**

   This chapter presents the background of the research and the storm water management facilities in townships. In this chapter, the problem statement is defined and the objectives of the study are set out.

ii. **Chapter 2: Literature review**

   This chapter presents literature review of previous research done on pervious pavements. The existing storm water facilities & open spaces including their use in the study area as well as Local government land use scheme in township development is also reviewed. The literature review looked into various types of pervious pavements, their applications and effectiveness as well as their advantages and disadvantages.

iii. **Chapter 3; Methodology**

   In this chapter, the methods used to achieve the objectives of the study are clearly outlined. The methods used include field data collection and conducting a series of laboratory tests of various types of pervious pavements to establish their effectiveness with regards to infiltration and susceptibility to clogging.

iv. Chapter 4: Results analysis

In this chapter, the results of the research obtained in chapter 3 were analysed. These results together with data obtained from chapter 2 were analysed with the view to establish a suitable pervious pavement for township development. Data analysis includes graphical presentation of test results and compares the data to find out which pervious pavement presents best option and to what scale.

v. Chapter 5: Conclusions and recommendations

In this chapter, conclusion based on research results was made, to determine the pervious pavement type best suitable for storm water management system for township development. The system integrates available land use in order to have a sustainable integrated storm water management system, which seeks to address the storm water social and economic challenges in townships. Future research recommendations are also presented in this chapter.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Up to year 2018, more than half of the world's population live in urban areas due to rapid urbanisation and as a result the urban green and open spaces in many developing countries are rapidly being affected (Qin *et al.,* 2018; Barau, 2015). In Africa alone, urbanisation which is the migration of people from rural areas to urban areas is increasing at an alarming rate forcing people to live in slums and occupying open spaces creating densely populated informal and/or formal settlements with hardened surfaces (Teye, 2018). The main drivers of this are; poverty, un-employment and social economic challenges people experience (Xie, *et al.,* 2019; Rahn, *et al.,* 2017; Dodman, *et al.,* 2019). This creates a huge demand for infrastructure (Cobbinah, *et al.,* 2015) and in response, the governments building more infrastructures including road network encroaching into open green spaces (Zeng, *et al.,* 2019). This is severely affecting urban resources more so the environment and the urban ecosystems (Xie, *et al.,* 2019; Rahn, *et al.,* 2017; Marsal, 2016; Elmqvist *et al.,* 2015).

South Africa is one of the many African countries facing the challenge of urbanisation in addition to high un-employment rate, poverty and slow economic growth (Arndt, *et al.,* 2018). This scenario according to Arndt, *et al.,* (2018), increased in the last two decades by the year 2018, creating high demand for urban resources. In order to meet the increasing demands for urban resources and infrastructure, new infrastructure is built and the existing infrastructure is expanded (Marsal, 2016). This results in increased impervious pavements/surfaces affecting the green areas causing environmental degradation and flooding during heavy storms (Xie, *et al.,* 2019; Marsal, 2016). These impervious/hardened surfaces in watersheds without meaningful storm water controls, result in increased storm runoff, peak flow flooding and decreased ground water recharge (Lindow, *et al.,* 2015). Floods are one of the most hazardous natural occurrences causing damages to infrastructure and in some cases loss of lives (Ahn, *et al.,* 2014). They have negative impact on the environment, urban ecosystem, municipal infrastructure and private property (Miller and Hutchins, 2017; Lindow, *et al.,* 2015). Sadly, the urban communities especially those living in densely populated informal and formal settlements are the ones who are heavily affected (Xie, *et al.,* 2019; Miller and Hutchins, 2017). These floods cause serious damage to infrastructure and cause loss of life in some cases (Singh, *et al.,* 2018).

South Africa is one of many countries in the world affected by flooding. Its urban areas including formal and informal settlements experience devastating flooding every year (Dalu, *et al.,* 2018). Alexandra Township, Johannesburg City centre and Diepsloot Township are some of the many areas affected by flooding as reported by Ra'eesa, (2016). The devastating floods destroyed municipal infrastructure and many shelters, leaving a number of people stranded. This is just one example of many floods experienced in various townships where infrastructure and lives are lost. This has to be addressed and it is becoming more necessary to re-look at the urban cities and settlement areas planning (Marsal, 2016).

Sustainable Urban Drainage Systems (SUDS) which include; detention ponds, pervious pavements and green roofs is one way to address the problems of flooding (Nnadi *et al.,* 2015; Deng *et al.,* 2013; Tixier *et al.,* 2011). These facilities range in sizes from very large structures to simple household/backyard facilities depending on the catchment area of the storm water runoff (Dreeli *et al.,* 2006). The design choice for the type of any SUDS to be installed in an area depends on several factors and has to be critically evaluated in order to arrive at a choice that will best serve the purpose and be sustainable (Deng *et al.,* 2013; Dreeli *et al.,* 2006; Tixier *et al.,* 2011).

Deng *et al.,* (2013) explains some of the factors to be considered in pervious pavement design and these are; value for money, available open space and opportunity cost of the system. Other factors to consider are; soil type and topography of an area (Dreeli, *et al.,* 2006). Furthermore, it is critical to assess the type of pervious pavement selected against the existing social, economic and physical conditions of the area for it to be economically viable, socially accepted and environmentally sustainable (Marlow, *et al.*, 2013). Pervious pavements become successful and sustainable if there is a buy-in from the community (Lin and De Meulder, 2012). This can be achieved by involving the community in planning and implementation of the project, using participatory or partnership approach method from the inception stage of the project (Barau, 2015). Therefore, it is important to involve communities when implementing pervious pavements and any other SUDS project especially in a densely populated area. Once communities are involved, from the beginning, they embrace the system as theirs and increasing community involvement in maintenance and reduce vandalism.

Barau (2015) conduct a research in a densely populated Malaysia community to establish their perception of green living. He concluded that communities appreciate green natural resources and would welcome such resources. His study, though it was for a specific area in Malayisa, it becomes significant in the sense that it involved densely populated communities similar to the communities in South Africa formal and informal settlements. In his research, he concluded that, once the communities are involved from the start of the project, they embrace it minimising vandalism of the system. He further, concluded that communities get involved in maintenance of the system, hence, prolonging its life span. In addition, Lindow, *et al.,* (2015) suggests that storm water runoff and peak flow flooding are reduced by using pervious pavements in watershed areas.

2.2 Pervious pavements structure and water storing mechanism

Pervious pavements also referred to as permeable pavements are used for storm water management designed specifically to manage the quantity and quality of storm water (Bruinsma *et al.,* 2017). These pavements consist of a multi-layered structure namely wearing course (surfacing), base layer combined with sub-base layer used as reservoir and sub-grade layer/in-situ material (Zhi *et al.,* 2012; Furgason, 2006). Each layer is multi-functional and it can be given alternative materials and configurations by applying the same physical principles that apply in impervious pavement designs such as traffic loading (Bruinsma *et al.,* 2017). They are designed and constructed to allow storm water runoff to infiltrate through the surfacing layer and temporarily stored in the base layer before it further infiltrates into the sub-grade layer/in-situ material or collected/harvested (Bruinsma *et al.,* 2017; Furgason, 2006). Over and above managing storm water, they also provide a rolling surface for vehicles just like in conventional flexible/rigid pavements (Hammes, *et al.,* 2018).

Pervious pavements allow storm water runoff to infiltrate through its layer preventing ponding water which is a hazard to motorists (Bruinsma *et al.,* 2017; Lindow, *et al.,* 2015). The storm water runoff rapidly infiltrates through either pervious pavement's joints (i.e. pervious interlocking paving blocks) or its porous structure (i.e. porous concrete and or asphalt), through to the underlying layer (base layer) instead of flowing on its surface (Chopra, *et al.,* 2011). The base layer with high void ratio is made of open graded crushed aggregate and it temporarily stores the infiltrated storm water before it infiltrates into the sub-grade/in-situ material or collected through pipe system for further use (Furgason, 2006). The base layer thickness is determined by structural and hydrological design analysis (Bruinsma, *et al.,* 2017). Figure 2.1 depicts a typical cross section of a pervious pavement.

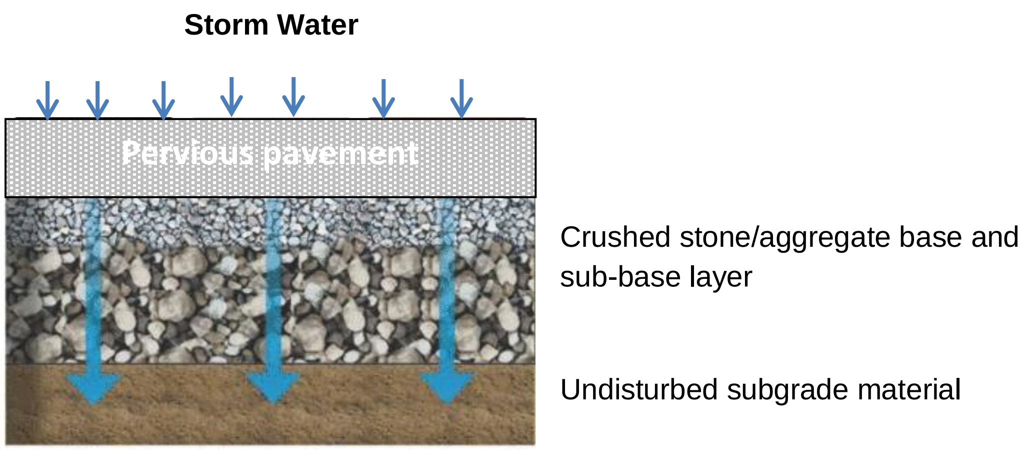


FIGURE 2.1: Typical cross section of a pervious pavement.

Source: Airport Cooperation Research Program (ACRP) Research Report 178 (2017).

2.2.1 Types of Pervious pavements

There are different types of pervious pavement with wide range of applications, each with its own advantages and disadvantages depending on the application (Lindow, *et al.,* 2015; Kayhanian *et al.,* 2019). All these types of pervious pavements are categorised differently although they can be one of the three systems commonly known as full infiltration pavements, partial infiltration pavements and or no-infiltration pavements (Kayhanian *et al.,* 2019; Bruinsma, *et al.,* 2017; Lindow, *et al.,* 2015). According to Bruinsma, *et al.,* (2017), these three pavement systems depicted in Figure 2.1 are described as follows:

i. **Full infiltration pavements**

This system directs storm water through the base and sub-base layer used as a reservoir and infiltrates into the underlying in-situ sub-grade material. This system is suitable in areas where the in-situ sub-grade material is highly permeable. The system is beneficial in re-charging ground water aquifers.

ii. **Partial infiltration pavements**

This system requires an additional drainage system in addition to the base layer (reservoir) which allows partial infiltration of water into the sub-grade layer. The storm water temporarily stored in the base layer is drained out through a pipe system or other drainage system such as gravel filled channels to a disposal or collection point.

iii. **No-infiltration pavements**

This system restricts storm water from infiltrating into the underlying sub-grade layer. An impermeable liner is installed on the sides and bottom of the base layer to stop storm water from infiltrating into the sub-grade layer. This system is required when sub-grade layer has very low permeability and also when preventing storm water from contamination ground water.

Figure 2.2 depicts typical cross sections for three types of pervious pavement surfaces and structure while Figure 2.3 depicts three types of how the storm water infiltrates into the existing sub-grade layer or harvested for further use.

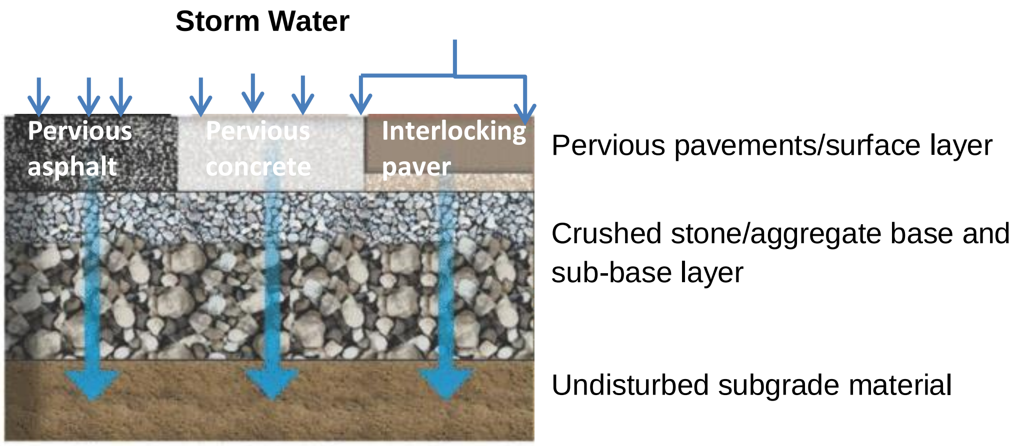


FIGURE 2.2: Three types of pervious pavement surfaces and structure.

Source: Airport Cooperation Research Program (ACRP) Research Report 178 (2017).

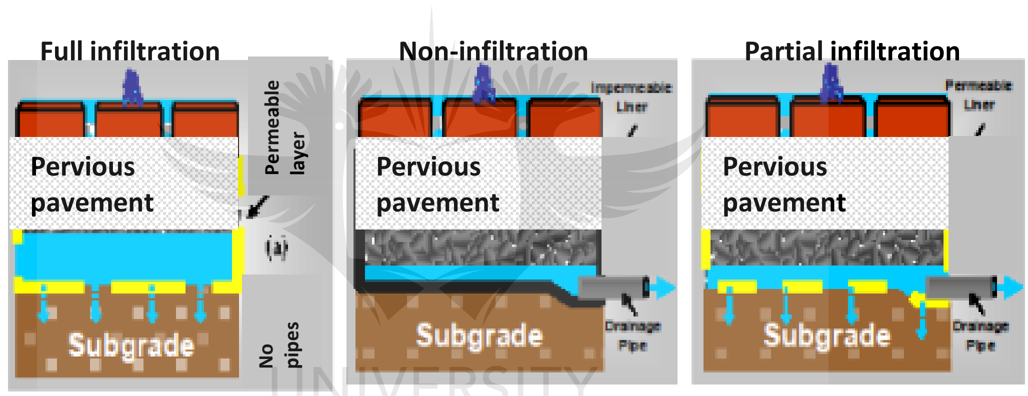


FIGURE 2.3: Three types of how storm water is collected

Source: Pervious Pavements: Water Sensitive Urban Design Technical Manual Greater Adelaide Region (2010)

Typically, different pervious pavements can be grouped into four namely; porous asphalt, pervious concrete, permeable interlocking blocks pavements and others such as grid pavement systems (Bruinsma *et al.*, 2017). All these pervious pavements fall under two categories and both categories play a significant role in managing urban storm water quantity and quality (Yong *et al.*, 2013; Lindow, *et al.*, 2015). These categories, relate to the wearing course/surface layer, can be grouped as follows:

i. **Porous pavements**

These pavements comprise a surface layer of highly porous material to allow filtration of water to underlain structure. The pervious asphalt or pervious concrete belong to this category.

ii. **Permeable pavements**

These pavements comprise a surface layer of pervious interlocking paving blocks which is typically impervious in nature and it is specially shaped to allow the ingress of water in between the joints. Other paving blocks maybe slotted (vertical slots) or shaped in a manner that once laid, they leave gaps which are gravel-filled or aggregate-filled to allow infiltration of storm water. Detailed discussion of this type of pervious pavement is under sub-section 2.2.1.2.

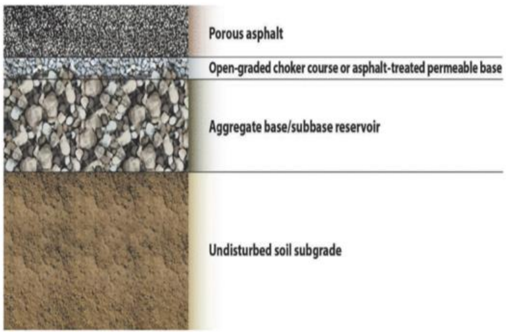
Both categories of the wearing course/surface layer have underlain common feature which is sub-base and base layer consisting of crushed stone or gravel to temporarily store storm water (Bruinsma *et al.,* 2017; Furgusson, 2006).

2.2.1.1 Pervious pavements

Pervious pavements, as previously indicated comprise a surface layer of highly porous material either asphalt or concrete to allow filtration of water to underlain structure (Yong *et al.,* 2013). Although other literature refers to pervious concrete as porous concrete, it falls under the category of pervious pavements. Sometimes it is termed as no-fines concrete even though it consists a small percentage of fines in the concrete structure. However, it contains same basic components as standard Portland Cement Concrete (PCC) but only contains smaller percentage of fines, and it is designed to have high porosity; with interconnected void content ranging from 11% to 35% depending on the percentage of fines added (Grubesa, *et al.,* 2018; Bruinsma *et al.,* 2017).

Similarly, pervious asphalt contains conventional hot/warm mix asphalt with significantly reduced fines content to have high interconnected void ratio ranging 18% to 25% (Bruinsma *et al.,* 2017; Chopra *et al.,* 2011). In order to improve its durability and prevent a possibility of binder drain out additives and high grade binders are used (Bruinsma *et al.,* 2017). It is also a common practice in other parts of the world to construct a pervious asphalt layer ranging between 50 – 80mm thick on top of the existing pervious concrete pavement to reduce traffic tyre noise (Kayhanian *et al.,* 2019). Other permeable pavements are made of plastic open-celled pavers. These paving units have the cells or openings penetrating the full thickness of the paving block so that they accommodate aggregate through which storm water infiltrates (Bruinsma *et al.,* 2017).

Figure 2.4 shows water infiltrating into pervious asphalt layer and Figure 2.5 shows pervious concrete.



Typical cross section of porous asphalt pavement

Source: Airport Cooperation Research Program (ACRP) Research Report 178 (2017).

FIGURE 2.4: Pervious asphalt layer

Source: Permeable Pavements book by Lindow, K. C., Smith, D. & Eisenberg, B. (2015)

FIGURE 2.5: Pervious concrete layer and structure

Source: Final report: Pervious pavements – Installation, Operations and Strength Part 1: Pervious concrete systems, Chopra, et al., (2011)

According to Chopra, *et al.* (2011), the strength of pervious pavements especially pervious concrete, depends on its material compressive and flexural properties together with the strength of the supporting underlying subgrade material. The structure of pervious concrete contains high void ratio by nature in order to achieve high permeability (Chopra, *et al.,* 2011). This results in having its compressive strength and flexural strength both compromised and lower when compared to conventional impervious PCC (Cosic, *et al.,* 2015; Chopra *et al.,* 2011). Cosic, *et al.* (2015) investigated the influence of aggregate type and size on properties of pervious concrete. One of the findings of the investigation was that pervious concrete does not satisfy the requirements for 28-day pavement concrete strength which ranges between 25MPa and 60Mpa, and it is only suitable to carry lighter vehicular loads.

To mitigate or overcome this barrier of lower compressive strength and flexural strength, Saadeh, *et al.,* (2019) conducted field and laboratory research on application of fully permeable pavements as a sustainable approach for mitigation of storm water runoff. The research was done on pervious asphalt and pervious concrete. The conclusion was that it is possible to design, develop and implement a fully permeable pavement system as a sustainable road transport system for freeways exposed to high axle loads to mitigate effects of storm water. Kayhanian, *et al.,* (2019) also conducted a field and laboratory tests on the use of various pervious pavements namely; pervious concrete, pervious asphalt and pervious interlocking concrete paving blocks, on highways in California. The research results confirm Saadeh, *et al.,* (2019) results that pervious pavements can be used in freeways for various environmental and economic benefits. The research findings show that pervious asphalt performed better when exposed to high axle loads than pervious concrete and interlocking paving blocks.

Furthermore, there are five distinct findings from Kayhanian, *et al.* (2019) research with regards to hydraulic performance evaluation. These are as follows:

i. The minimum aggregate base thickness sufficient to capture all rainfall over a 24 hours natural rainfall with return periods ranging from 2 years to 100 years should be in the range of 0.15m, with a maximum of 2.9m. This however, depends on various factors such as slope, underlain soil type and rainfall intensity.
ii. The required minimum aggregate thickness in high rainfall areas is 50% more than, but within the above-mentioned range of layer thickness, the minimum required for areas with medium rainfall.
iii. The storms with longer recurrence periods (50 – 100 year) require thicker base layers compared with storms with shorter recurrence periods (2 – 5 years) with similar aggregate size of the base layer. A recurrence period of 2-5 years with a rainfall intensity of minimum 15 minutes is appropriate for roads/streets design in townships.
iv. Permeability decreased after several repetition of traffic loading mainly due to clogging and minor rutting on pervious asphalt.

2.2.1.2 Permeable pavements

Permeable pavements are generally constructed using impervious concrete or clay paving blocks specially shaped to allow the ingression of water in between the gaps and joints (Lindow, *et al.,* 2015; Furguson, 2006). Figure 2.6 shows a surface of the pervious interlocking paving block with gaps in between for storm water infiltration. The mix designs of permeable pavements (i.e. wearing course constructed using pervious concrete or pervious interlocking paving blocks) is to withstand traffic loads including heavy traffic and are usually 80mm thick (Furguson, 2006). The same thickness requirement is also confirmed by (Kayhanian, *et al.,* 2019).

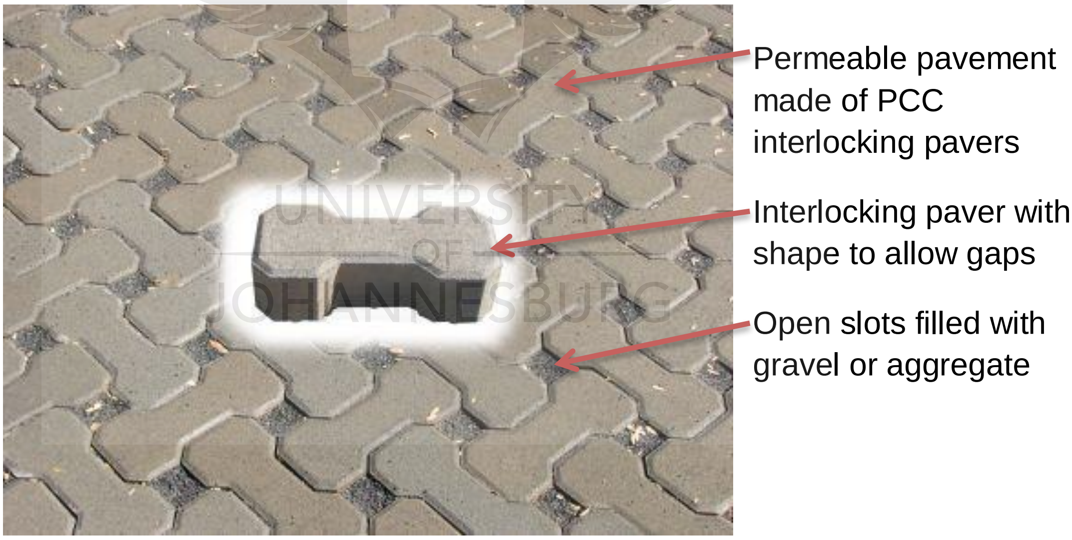


FIGURE 2.6: Pervious interlocking pavers

Source: http://www.vanstone.co.za/80mm_aqualock_pavers

Permeable pavements are able to reduce or even prevent storm water runoff, peak floor flooding and to same extent heat island effect (Qin, *et al.,* 2018). They have an effective permeability which can reach up

0.01L/s provided they are constructed with gravel chips having 2-5 mm drainage openings between them (Qin, *et al.,* 2018; Lindow, *et al.,* 2015). They can maintain this type of permeability for at least 5 years provided a good pavement maintenance programme is put in place (Lindow, *et al.,* 2015).

In practice, infiltration rate dependent on many factors, mostly it is the degree of clogging which is often related to the age of the pavement and the degree of storm water quality especially suspended solids (Yong *et al.,* 2013; Sasalone *et al.,* 2012). The other factors to consider for sustainability of permeable pavements are; avoiding steep longitudinal slopes of the pavement to avoid over concentration/loading of storm water on the lowest point of the pavement if it is designed to allow filtration of storm water into the underlying material. The other factors are the use and type of geofabric layer as a sub-base or base layer liner which can reduce the infiltration rate to as low as 2 millimetres/hour if storm water is required to be harvested through pipes and sub-grade soil infiltration rates (Qin, *et al.,* 2018). The operational considerations are; maintenance, rehabilitation, social requirements and overall safety consideration (Qin, *et al.,* 2018; Kamali, *et al.,* 2017; Lindow, *et al.,* 2015). To address these factors, more specifically the slope, it is necessary to develop integrated storm water management systems which include permeable pavements and other SUDS such as detention ponds system to allow flow of collected storm water by gravity to detention ponds through subsurface pipe network (Qin, *et al.,* 2018).

Permeable pavements have comparable advantages over porous pavements (Kayhanian, *et al.,* 2019; Jamshidi, *et al.,* 2019; Furguson, 2006; Lindow, *et al.,* 2015). These are as follows:

- They do not have surface layer rutting problems
- Easy maintenance to prevent and remove clogging. It can also be rapidly maintained or rehabilitated in an event of structural damage because there are no binding materials in between joints such as bitumen or cement.
- They are suitable for use in residential streets and overall generate more employment opportunities during construction or maintenance.

2.2.2 Pervious pavements design consideration

Designing pervious pavements requires taking into account certain parameters and conditions such as traffic loading, Infiltration rates of the materials used, climatic conditions, site soil conditions, topography of the area and storm water disposal requirement for it to perform as expected (Bruinsma, *et al.,* 2017; Zhi, *et al.,* 2012; Furgason, 2006). There are also some specific considerations and factors to be fulfilled when designing pervious pavements. Some of these design conditions and factors according to Lindow, *et al.,* (2015) include the following:

- **Subgrade stability:** The subgrade layer should be stable enough to prevent collapse of the pavement. If the subgrade material is not stable such as collapsible sand materials, the pavement structure may fail.

- **Permeability of the subgrade layer:** The subgrade layer should have adequate permeability to allow infiltration of storm water. Pervious pavements cannot effectively perform in areas with high water table.
- **Pre-treatment of runoff where necessary:** Some storm water runoff carry sediments and contaminants which could easily cause clogging even if there is maintenance in place. For example, storm water runoff contaminated with oils and grease from fuel service stations and or parking lots. These should have pre-treatment facilities installed before the storm water gets discharged into the pervious street/road.
- **Slope to manage flow:** For pervious pavements designed to allow infiltration of storm water into the underlying/sub-grade material, the slope should be relatively flat. For pervious pavements designed to harvest storm water for other uses or discharge into a natural water course, there is a need to have adequate rolling slopes to allow gravitational flow of storm water to a discharge or collection point. Both designs must have a surface which is relatively flat or as close as possible to being flat in order to have a uniform and distributed flow coverage to prevent hydraulic overloading on one portion of the surface.

- **Overall structural integrity of the pavement:** The pervious pavement should be able to carry expected traffic loading and environmental stresses without failure.
- **Safety consideration:** Safety is paramount. Pervious pavements should be designed to meet safety standards and guidelines, as for conventional pavements.
- **Clogging consideration:** This is a major problem in pervious pavement's life performance. There should be a clear and adequate operation and maintenance programme put in place to minimise clogging.

All these conditions and factors are considered during field data collection and desk top survey of literature (Lindow, *et al.,* 2015; Chopra *et al.,* 2011; Furgason, 2006). Lindow, *et al.,* (2015), recommended that field inspection phase to include data such as soil subgrade conditions, underground structures & utilities, land use & contamination potentials and land topography/terrain.

2.2.3 Benefits of pervious pavements

Pervious pavements in general whether porous or permeable offer a wide range of benefits which include environmental, operational and economic benefits compared to impervious pavements (Xie, *et al.,* 2019; Rahn, *et al.,* 2017; Bruinsma *et al.,* 2017). The benefits are as follows:

i. Environmental benefits

Various research indicated that pervious pavements to be overall environmentally friendly and provide the following benefits:

- Reduction or even zero storm water runoff quantities and peak flow flood by providing retention/detention storage capacity and reducing flow velocities.
- Increased groundwater recharge and improves the quality of storm water when it infiltrates through an underlying bedding and base course media. This action removes some sediments and solids which include inorganic and organic pollutants
- Overall, they are environmentally sustainable.

ii. Operational benefits

- Prevent accumulation of storm water on the surface of the pavement, hence, increases skid resistance during storm periods. This makes riding during storm periods easier and safer.
- There is no risk of icing on top of the pavement surface because water does not accumulate on the surface. Therefore, the risk of skidding is reduced.

iii. Economic benefits

- The harvested storm water runoff from the sub-base/base layer can be re-used for irrigation or other purposes which generate income for the end user/community.

Although pervious pavements have great benefits, it is important to note that they have some shortcomings associated with operations and maintenance if not properly managed. However, the benefits outweigh the shortcomings (Xie, *et al.,* 2019; Zhang *et al.,* 2018; Yong *et al.,* 2013; Sasalone, *et al.,* 2012).

2.2.4 Shortcomings of pervious pavements

Previous studies on pervious pavements identify clogging as the major long term shortcoming/problem if necessary maintenance procedures are not put in place (Zhang *et al.,* 2018; Chopra, *et al.,* 2011). The other factors affecting performance of pervious pavements are porosity, permeability, freeze-thaw and chemical attack. The effect of these factors can be mitigated and addressed through mix composition at design stage. (Zhang, *et al.,* 2018; Yong *et al.,* 2013; Sasalone, *et al.,* 2012). Clogging, being the operations and maintenance factor affecting performance and durability of pervious pavements, it is addressed further in this study.

Clogging in pervious pavements which is a term used to describe the performance of a pervious pavement when its hydraulic performance drops over a period of time needs to be managed properly to maintain its desired hydraulic performance (Yong, *et al.,* 2013). Clogging happens when solids in storm water accumulate in the pores of the pervious pavement and hinders infiltration of the storm water through the pervious pavement. It may be caused by slow siltation process or rapid siltation process which is triggered by a sudden slump or landslide (Zhang *et al.,* 2018). Management of clogging is done through maintenance using various techniques (Zhang, *et al.,* 2018) such as frequent mechanical booming, wet or dry vacuuming of the pavement or cleaning the pavement aggregates by firstly removing the pervious interlocking paving blocks (Bruinsma, *et al.,* 2017; Chopra, *et al.,* 2011).

Zhang, *et al.,* (2018) and Yong, *et al.,* (2013) carried out laboratory experimental studies on predicting clogging in porous pavements. They concluded that clogging is affected by factors such as road gradient and aggregate size. Various research concludes that clogging gets concentrated on the top 0mm to 30mm pavement layer including the geotextile layer of the permeable pavers pavements while the underneath layer beyond the 30mm clogging is almost zero (Zhang, *et al.,* 2018; Yong *et al.,* 2013; Chopra, *et al., 2011*). This is key element to advance the maintenance requirements of pervious pavements since maintenance is recommended as the key to keep the performance of pervious pavements alive and extend their performance life (Chopra, *et al.,* 2011). The frequency of maintenance varies depending on the type of pervious pavement, though Sasalone, *et al.* (2012) recommends quarterly maintenance frequency.

2.2.5 Effectiveness and efficiency of pervious pavements

The effectiveness and efficiency of pervious pavements in management of storm water hinges on two main factors namely its infiltration rate and water storage capacity base layer (Grubesa, *et al.,* 2018). The infiltration rate of storm water is based on the void ratio of pervious pavement surface and structure. The high void ratio allows storm water to infiltrate at a faster rate preventing or reducing surface runoff and or peak flow flooding (Kayhanian, *et al.,* 2019; Saadeh, *et al.,* 2019; Zhu, *et al.*, 2018).

According to Lindow, *et al.,* (2015), pervious pavements can improve the water quality of storm water runoff through the following processes:

- Filtration through the pavement layers and underlying material, which can physically remove pollutants.
- Potential biological activities within the pavement layers and sub-grade material.
- Reduced runoff volumes entering water bodies reduces overall pollutants.

The infiltrated storm water gets stored temporarily in the base layer and later infiltrates into the underlying soil or gets collected through pipes for other uses. The effectiveness of the base layer storage capacity depends also on aggregate void ratio and its thickness not necessary the type or shape of the aggregate used (Kayhanian, *et al.* 2019; Grubesa, *et al.,* 2018). If the void ratio is kept constant during the pavement life, a thicker base layer stores more storm water than a thinner base layer (Kayhanian, *et al.* 2019).

In order to maintain the effectiveness of pervious pavements, it is important to prevent clogging by implementing regular maintenance by removing particles from the surface of the pavement (Koohmishi and Shafabakhish, 2018). Pervious pavements are mostly effective in removing sediments mainly coarse to medium and attached pollutants such as nutrients, free oils/grease and metals (Lindow, *et al.,* 2015). Table 2.1 summarises the effective void ratio and base layer thickness of a pervious pavement according to Kayhanian, *et al.,* (2019) and Grubesa, *et al.,* (2018).

TABLE 2.1: Effective void ratio range and base layer thickness.

Item description	Range
Void ratio	11% to 35%
Base layer thickness	150mm to 2 900mm

Thinner base layers do not store enough storm water to effectively reduce or avoid surface runoff and or peak flow flooding. On the other hand, very thick base layers become un-economical and should be avoided where possible.

A properly designed and constructed pervious pavement can achieve efficiencies shown in Table 2.2 in removing sediments and attached pollutants from storm water (Lindow, *et al.,* 2015).

TABLE 2.2: Performance efficiencies of pervious pavements

Coarse sediment (0.5-5mm)	Medium sediment (0.06-0.5mm)	Fine sediment (<0.06mm)	Free oil & grease	Total Nitrogen	Total Phosphorous	Metals
50-80%	30-50%	30-50%	10-50%	40-80%	50-80%	10-50%

2.3 Detention ponds in storm water management

Storm water detention ponds are designed to store and release the storm water runoff of extreme rainfall events based on a selected return period such as 2 years, 5 years etc. (Elshorbagy, *et al.,* 2018). For many decades, detention ponds have been used in storm water management to avoid peak flow flooding (Hong, 2010). These detention ponds can be large or small in sizes depending on the area/region where they are used. They also help in reducing pollution levels in storm water during the period the storm water is stored in the pond, suspended pollutants settle to the bottom (Kebler, *et al.,* 2017).

In addition to storm peak flow flooding, detention ponds have ecological benefits as well as environmental benefits and can be used in conjunction with pervious pavements in managing storm water flows to maximise these benefits (Miro, *et al.,* 2018). This can be done by directing the temporarily stored (harvested) storm water from pervious pavements to the detention ponds and later used for other purposes such as irrigation, and or recreation in addition to ground water recharge (Xie, *et al.,* 2019; Miro, *et al.,* 2018; Rahn, *et al.,* 2017). Furthermore, harvested storm water can also be purified and used for toilets flushing in some cases (Hammes, *et al.,* 2018).

Although the use of storm water harvested from pervious pavements requires an initial investments of installation of pipes, filters, tanks, detention ponds, etc, there are long term benefits to society, cities and the environment which out way the initial investment (Hammes, *et al.,* 2018). Hence, integrating the use of pervious pavements and detention ponds in storm water management would maximize long term benefits.

Detention ponds whether small or large can be used as SUDS in any area regardless of the social economic status of the community (Miro, *et al.,* 2018). These ponds can be used as nature based solutions in storm water management to promote and address human health and wellbeing alongside biodiversity, social and un-employment challenges in established cities/communities (Jamshidi, *et al.,* 2019). In order for this to succeed it is important to approach it in a co-ordinated manner that include key stakeholders which are, government spheres and communities (Jamshidi, *et al.,* 2019; Kayhanian, *et al.,* 2019; Zhong, *et al.* ,2018).

2.4 South Africa Integrated Development Plan (IDP)

The majority of countries worldwide are recognising the need for regulatory changes required to solve storm water runoff challenges in areas faced with urbanization problem, and a retrofit technique where there are impervious pavements in developed areas (Sun, *et al.,* 2019). These regulatory changes require the management of urban storm water to move away from the traditional systems for disposal of storm water to a philosophy that integrates a range of distributed, multi-functional elements of storm water management (Segaran, *et al.,* 2014).

According to Section 25 of the South Africa Local Government: Municipal Systems Act, 2000 (Act 32 of 2000), each municipal council must, after the start of its elected term, adopt a single, inclusive and strategic plan called Integrated Development Plan (IDP). This is for the development of the municipality to link, integrate and coordinate plans and take into account proposals for the development of the municipality and which aligns the resources and capacity of the municipality with the implementation of the said plan.

Since the municipalities are responsible for township development and provision of various municipal services including roads, an Integrated Development Plan is a brilliant plan that gives an overall framework for inclusive and coordinated development. This is important because in the past researchers and pavement materials experts focused exclusively on the structural strength of pavement materials, without paying sufficient attention to the environment, cultural norms and community needs at large (Jamshidi, *et al.,* 2019). According to Jamshidi, *et al.,* (2019), it is necessary to develop an integrated municipal infrastructure system that addresses the new requirements owing to the environmental challenges, social requirements, aging population, and un-employment. The IDP fits well with these new requirements and the inclusion of land use in storm water management system would alleviate un-employment in townships.

The pervious SUDS which integrate land use will be in line with South Africa Integrated Urban Development Framework (IUDF) urban policy. This framework is a central platform to guide the nation towards transformation of all municipal spaces into liveable, safe, resource efficient cities and towns that are socially integrated, economically inclusive and globally competitive (CoGTA, 2017 and GoGTA, 2018). This will in turn improve the quality of life for many people living in townships, which is one of the primary objectives of the IDP according to the Municipal Systems Act, (2000). This is so because it takes into account the existing conditions, problems, resources, economic and social development available for development in an area as a whole.

2.5 Major findings from literature review

The worldwide problem of urbanisation creates un-intended environmental consequences through occupation of urban green spaces. As a result of that, more impervious pavements are built to cope with increasing infrastructure demand, due to increasing urban population. Furthermore, more road network with impervious surfaces is constructed for economic development/growth. These impervious pavements/surfaces fundamentally alter the natural processes of the water cycle exhibited in a natural environment.

In a natural state/environment, rain falls onto earth and immediately infiltrates into the ground to become ground water and some of it is stored in depressions, lakes, rivers and dams to become surface water. Infiltration of the surface water stored in depressions, lakes, dams and rivers continues while some of it evaporates back into the atmosphere and the cycle continues. The current state of this cycle where there is urban development affects this process of water cycle due to the vast impervious pavements/surfaces constructed. These surfaces do not allow the natural filtration of water into the earth.

These impervious pavements/surfaces cause storm water runoff and peak flow flooding with devastating effects to the environment and human life. There is enough evidence from literature review that, the solution to this problem is to start using pervious pavements/surfaces as opposed to impervious pavements/surfaces, because they allow storm water to infiltrate through their surfaces and as a result drastically reduce surface runoff and peak flow flooding. Furthermore, pervious pavements/surfaces reduce the concentration of solids and heavy metal in storm water resulting in having less contaminated storm water entering the natural water resources especially ground water.

Pervious pavements/surfaces have great environmental, operational and economic benefits even though some literature suggests that their use remains limited to parking lots, road side walks, pathways and light trafficked roads. This limited use suggested by some literature is due to some drawbacks inherited from their limited strength and susceptibility to clogging. However, in the recent years, this attracted renewed research interests into finding solutions to improve their strength and long term sustainability. The renewed research has proven that the use of pervious pavements is not limited to only parking lots, road side walks, pathways and or light trafficked roads. Evidence from renewed research indicate that their compressive strength of pervious concrete and pervious interlocking paving blocks can be improved through the incorporation of supplementary cementitious material such as Silica fume and their long-term sustainability can be achieved through regular maintenance.

However, there is still a need for further research on the use of these pervious pavements integrated with other SUDS systems such as detention ponds in townships to mitigate the effects of peak flow flooding.

CHAPTER 3: METHODOLOGY

3.1 Introduction

The research using Diepsloot Township as a study area was designed to collect both field and laboratory data. Both field and laboratory data were necessary to establish which pervious pavement type is suitable for storm water management to reduce flooding in the township. The field data which involved ascertaining the street width, lengths, housing proximity to the streets and available open spaces was necessary, because one of the key drawbacks of pervious pavements is clogging which is caused by sand and silt collected by storm water run-off. Furthermore, in this research, the pervious pavements are required to be intergrated with detention ponds which require open spaces.

To complete the investigation, laboratory experiments to establish the effectiviness of various pervious pavements in terms of filtration were necessary. Labarotory experiments were conducted at the University of Johannesburg (UJ) Auckland Park campus laboratory. The laboratory experiments samples were collected from the commercial suppliers of pervious pavements around Johannesburg area.

3.2 Data collection

The data collection procedure followed was in two stages. The first stage involved field data collection. The second stage involved laboratory experiments.

3.2.1 Field data collection

The field data was collected from the study area namely Diepsloot. Field data collection started on 1st July 2019 and was completed on 30th July 2019. This period of the year is dry season in the said area, meaning that there were no rainfalls. The area is densely populated with houses very close to each other, in some cases next to the edges of streets as dipicted in Figure 3.1. Diepsloot is a formalised settlement in the Western Region of Johannesburg.

This township was established in 1995 as a temporary informal settlement/shelter (JRA, 2010). Formalisation of the towship started in 1999, firstly by establishing a transitional council to register all people in the area so as to start with developments.

3.2.1.1 Field research technique and design

The research technique involves actual measurements of the street and housing infrastructure, as well as open spaces. The measurements were recorded on specially design record sheets numbering each street measurement and its location. The field data was then transferred into computer software; microsft excel and average results including tables were produced.

Figure 3.1 is a cadestral view of a section of the study area. It can be seen from the figure that the houses in the area are close to each other and and at close proximity to the streets. In order to get the actual housing development layout, roads/streets network layout, shelters proximity to roads/streets, available open spaces and existing storm water management facilities, several field visits and measurements were done.

FIGURE 3.1: Cadastral view of a section in Diepsloot Township

(Source: Diepsloot storm water master plan (2010) by Civil Concepts (Pty) Ltd)

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3.2.1.2 Required field data

There are a number of factors to be considered during field data collections/investigations of pervious pavement installation. These factors can be grouped as follows:

- Soil subgrade sampling
- Underground structures and utilities
- Land use and contamination potentials
- Land topography/terrain
- Weather/rainfall data

The first two elements though required at design stage of pervious pavement, they were not investigated in this research. The focus was on the last three which affects the surface infiltration rate of pervious pavements. The factors investigated were; Land use & contamination potentials and land topography/terrain. The streets of the study area meet the requirements in terms of slope for pervious pavemnents. Therefore, the data collection streets were randomly selected from the entire study area. The following was measured:

i. Street width, length and terrain.
ii. Distance between the street edge and houses.
iii. Land use; size of available land and distance from the closest street(s).

(a) Street width and length

The selection of streets was done after subdividing the entire study area into 2 sections namely; Upper section and Lower section. These sections are divided by a stream as dipicted in figure 3.1.

A total of 16 streets were selected from the lower section of which 10 were selected from lower Northwest side and 6 from the lower Sourthern side. From the upper section, there were 14 streets selected. The lower section of the study area is more developed than the upper section, hence more streets were selected from lower section than upper section. The streets are surfaced with asphalt and the houses are built in a more systematic manner. The road infrustructure on the upper section is a mixture of surfaced roads with black top asphalt and gravel roads. Figure 3.2 shows how street/road length and width were measured.

FIGURE 3.2: Streets pictures from upper section.

During field data collection, storm water in some streets was observed flowing on the surface of impervious asphal as shown in Figure 3.2.

The vertical elevation of the streets/roads is level with existing ground level and in some cases slightly lower than the ground level. This is the standard practice for township road network infrastructure as opposed to freeways whose vertical elevation in most cases is raised above natural ground level. The streets/roads in a township are vulnerable to sand and silt deposits on the street/road surface. In order to mitigate this challenge, and control storm water surface runoff, curb are installed on the streets/roads edges, However, due to the nature of townships being densely populated, sand deposits still occur as it can be seen in figure 3.3. This is due higher activities by people on the ground surfaces caused by people either walking or working. Regular maintenance of streets is required to remove the sand and silt deposits.

FIGURE 3.3: Sand deposits on streets

Sand and silt deposits on streets/roads gets worse during heavy storms, because storm water runoff carries sand, silt and other solids from sorounding areas.

(b) Distance between the street edge and adjacent houses

The study area just like many townships in South Affrica is densely populated. The houses are close to each other and also close to the streets/roads. This scenario is worse on the upper section than the lower section as indicated in figure 3.4.

FIGURE 3.4: Streets pictures from lower and upper sections.

(c) Land use, available open spaces and distance from the street(s).

There are large sizes of open spaces, especially along the stream which are not used. Some of the open spaces are used as recreation parks. These spaces are ideal for installation of detention ponds, because they are situated on the lower side of all sections of the township. Harvested storm water from pervious pavement can gravitate towards detention ponds. There are also isolated small open spaces in between housing developments which can also be used for installation of localised detention ponds. Figure 3.5 shows some of the open spaces along the stream and in between houses. Along the stream, the open spaces are in excess of half a hector and can service both upper and lower sections of the township.

FIGURE 3.5: Open spaces available.

(d) Social economic challenges.

In general, townships in South Africa are faced with high unemployement and other social challenges such as drug abuse acording to Statistics South Africa, (2019). Furthermore, it is reported in Statistics South Africa, (2019), that the study area Diepsloot Township is one of the most affected townships in terms of unemployement.

3.2.1.3 Field data collection limitations

The data collection was carried out during winter as discussed in section 3.2.1. During this period, there are fewer rains in the area. Therefore, the effects of high storm water runoff and peak flow flooding were not seen first hand in the study area. Furthermore, the study area covers approximatly 1014.681ha with numerous streets and housing as it can be seen in figure 3.1. Not all streets were measured in the study area and there were no subgrade soil sampling and tests conducted. The data collection/investigation only focused on elements relevant to the study, which include land use & contamination potentials and land topography/terrain

3.2.2 Laboratory tests

Samples of various types of pervious pavements which represent typical designs used in practice as established in specific objective (i) were collected from the nearby commercial suppliers. The samples were cut to equal width & length and tested under same laboratory conditions. The selection of the material used to simulate the base layer was based on the previous research data from literature review. Crushed storn base layer is suitable for base layer and 19mm uniformly graded aggregate size was selected. It was obtained from a nearby commercial quarry. The same aggregate sample was used for all pervious pavement structures for the laboratory tests.

The following laboratory tests were done:

- **Filtration test:** This test was conducted to determine the infiltration rate of the pervious pavement samples using clean water from the tap. A falling head test method using ASTM standards was used. Each test sample was placed in a measurement marked container open on top and closed at the bottom with 30mm diameter valve. The aggregate was placed at the bottom and each pervious pavement sample was placed on top of the aggregate. The sides of the sample and container were sealed using silicone. At the start of the test, each pavement surface test container was filled with water up to a certain level/head. Water level was measured and recorded.
- **Clogging test:** Clogging test was conducted to determine which type of pervious pavement is more prone to clogging. A simple laboratory clogging test procedure using using ASTM standards and similar to the tests conducted by Yong *et al.,* (2013) to predict physical clogging of porous and permeable pavements was used. The tap water was mixed with clogging material (sand and silt) and allowed to filtrate through test samples. It was necessary to conduct this clogging test with local pervious pavements samples, in order to establish the

behaviour of these three types of pervious pavements under conditions similar to storm water. The tests procedure was similar to the test procedure done with clean water.

3.2.2.1 Apparatus/equipment used

The following apparatus and equipment were used:

- 3 No. x 112.6*l* capacity transparent plastic containers graduated in milimeters with 0mm at the top, sealed at the botton with a 30mm diameter openning. The containers are measuring 445mm x 550mm x 460mm. The opening at the bottom was connected to 30mm ID valves. The valves were used to drain water during filtration process. The 19mm single graded aggregate sample was placed at the bottom of the container occupying 100mm depth of the bottom section of the container. The same thickness for all tests was used.
- Pervious test samples namely; pervious asphalt, pervious conrete and pervious interlocking paving blocks were used. These samples were obtained from commercial suppliers and the sizes are as follows:
  - ➢ Pervious asphalt sample : 445mm wide x 550mm long x 40mm thick (See Figure 3.7a).
  - ➢ Pervious concrete sample : 445mm wide x 550mm long x 100mm thick (See Figure 3.7b).
  - ➢ Pervious interlocking pavers : 60mm thick layed to occupy 445mm wide x 550mm long (See Figure 3.7c).

- 1 No. flat table used as a platform for test containers.
- 3 No. x 65*l* containers used to collect drained infiltrated water through 30mm diameter flexible pipes connected to drain valves.
- 1 No. stop-watch (Volkano track series) was used to measure the duration of infiltration which was used to calculate the flow rate (infiltration rate) '*V*' using the formula in equation (1).

$Q = V/t$……………………………………………………………(1)

Where:

V = Volume of water received in the infiltration receiving chamber.

t = Time period measured to obtain the volume 'V' measured.

3.2.2.2 Test samples

The pervious test samples used are shown in Figure 3.6a, 3.6b and 3.7c. The thickness of test samples was based on the industry commonly used for pavement construction for each type of pervious pavement. However, the surface areas for all test samples exposed to water used for filtration were the same (0.245m^2). The aggregate used as filter bed was 19mm stones x 100mm thick for all tests.

FIGURE 3.6a: Pervious asphalt

FIGURE 3.6b: Pervious concrete

FIGURE 3.6c: Pervious interlocking paving blocks

The gaps on interlocking paving blocks were filled with 7mm aggregate as shown in Figure 3.7.

3.2.2.3 Test procedure

The test procedure followed was, firstly to set-up the apparatus/equipment in the university of Jahannesburg Laboratory. The apparatus/equipment and test samples described in sub-section 3.2.2.1 and 3.2.2.2 respectively were assembled.

The 112.6*l* capacity containers with valves of 30mm ID valves closed were placed on top of the table as dipicted in Figure 3.8. The 19mm aggregate were placed inside each container until there was 100m thick of aggregate in each container and were levelled. The pervious samples were placed on top of the aggregate inside the containers "test containers" and the edges were sealed with silicone to prevent water infiltrating between sample edges and container. In between large gaps of interlocking pavers, 7mm aggregate were place depicting the actual industry practice when pervious pavers are laid on a road. Figure 3.7 shows the pervious pavement test samples in containers and the edges sealed with silicon.

FIGURE 3.7: Sealing the edges with silicon.

The test containers were filled with clean water to the same level and the water levels were recorded for each test container. The 65*l* capacity empty containers were placed directly under each valve. To start the tests, all valves were openned at the same time and started running the stop watch. After 200 seconds for each test, the valves and stop watch were all shut at the same time and recorded the water levels in the test containers. This test procedure was repeated for each test done both for clean and sand & silt containinated water (clogging test). Figure 3.8 shows the test apparatus set-up. All three containers have the same surface area.

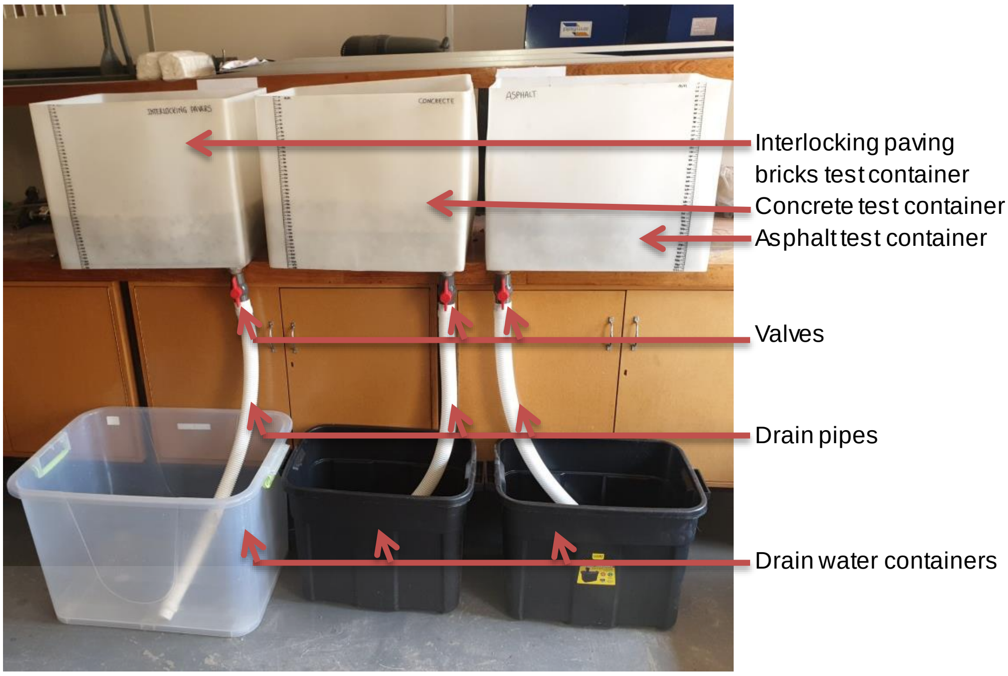

FIGURE 3.8: Test apparatus

3.2.2.4 Filtration tests

Filtration tests were done in two stages. The fist stage involved using clean tap water only. The second stage involved using clean water from the tap mixed with sand and silt as contaminant. This test was done to measure how clogging affects filtration on the three diferent pervious samples.

3.2.2.4.1 Filtration test using clean water

As started in test procedure section, the 112.6*l* capacity graduated transparent plastic containers, containing pervious pavement test samples were filled with clean water. The water level was the same for all three (3) containers. Once all containers were filled with water to the same level, the stop watch was started while the valves on drain pipes were simultaneously openned. The drop down filtration process started.

After 200 seconds of filtration before the water in the container reached the pervious pavement surface, the stop watch and the valves on drain pipes were shut all at the same time. The water levels on each container were recorded. The same procedure was followed for all series of filtration tests. A total of 16 same tests were conducted to validate the results.

The volume of filtered water for each test done was calculated and recorded. Thereafter, the filtration rates for each pervious pavement sample were calculated using the calculated filtered water volume and the recorded time of filtration which is 200 seconds for each test. All results were analysed to compare filtration rates of the three pervious pavement samples.

3.2.2.4.2 Filtration test using sand and silt contaminated water

The filtration test using sand and silt contaminated water was done to measure how clogging affects filtration rate. There are two types of sand used as clogging material. The first one is 0.5mm single gradded sand as shown on figure 3.9, the second one is silt like material shown on figure 3.10. The silt material was collected from study area Diepsloot Township existing roads surfaces in order to simulate clogged storm water from study area.

FIGURE 3.9: 0.5mm sand clogging material

FIGURE 3.10: Silt clogging material

Two similar sets of test were conducted in succession using contaminated water with the two different types of soils as clogging materials. The first test involved mixing 0.00138m^3 of 0.5mm single graded sand material with 0.0589m^3 of tap water per test. Six repeated tests were done in order to validate the results. The procedure followed and time of filtration is the same as in tests done using clean water. The filtered water volumes and filtration rates per test were calculated and results rocorded and plotted on graphs.

The second series of tests involved using silt like sand as the cloding material. The same procedure and filtration time as in first series of tests was followed. A total of six reapeated tests were done and calculated filtration results were recorded and plotted on graphs. Figure 3.11 shows test apparatus with water mixed with clogging sand.

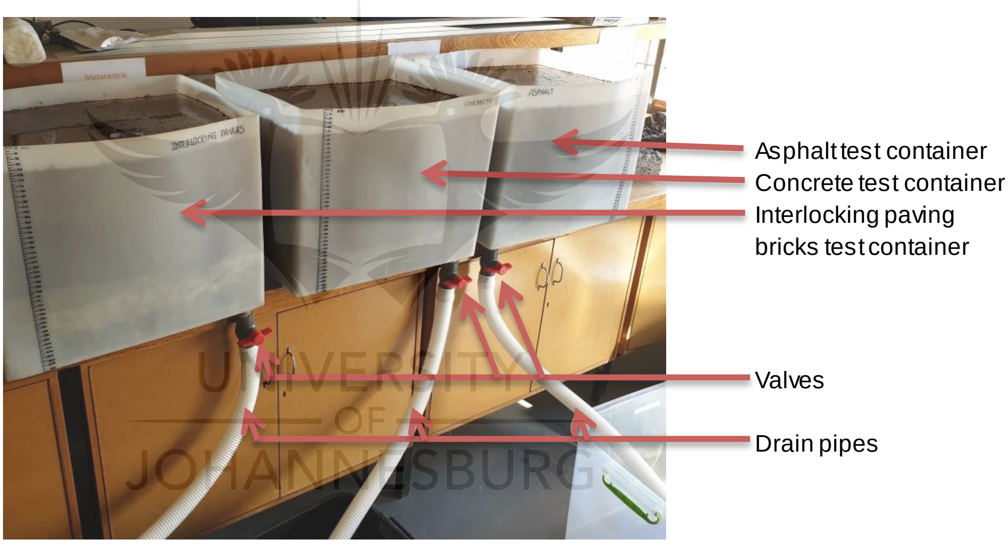

FIGURE 3.11: Clogging test

The tests were conducted one after the other per pervious sample test apperatus and the mixed sand was not removed from the test apparatus after each test. Therefore, there was cummulation of sand (clogging material) on the surface of test samples as indicated in Figure 3.12. The water used for filtration was drained into collection containers.

Clogging material (sand) accumulate on the surface of the pervious pavement sample

FIGURE 3.12: Silt clogging material on sample surface

The results obtained were recorded and filtration rates calculated. The filtration rates were plotted on graphs, compared and analysed.

3.2.2.5 Laboratory experiments limitations

The laboratory experiments were conducted at room temperature for all three test samples. However, the test samples were prepared at three different locations with varying temperature conditions but suitable for manufacture of the test sample itself. They were all cut to same sizes which are 445mm wide x 550mm long with different thicknesses. This was so because there are different commercial supliers of the three types of pervious pavement samples used and the test apparatus used could only fit 445mm x 550mm test samples. The thickness of each sample was equal to the industry general practice thickness for the particular pervious pavement. Furthermore, the test samples were not subjected to traffic loading. Due to different pervious thickness and same aggregate thickness of 100mm, the pervioyus surfaces were subjected to minor water head pressure. The maximum difference was 60mm which was between pervious asphalt and pervious concrtete. Tap water was used for filtration tests in both clean water tests and clogging tests.

3.2.2.6 Reliability and validity of data

It is important to ensure that the test apparatus are reliable. Reliable test apparatus will show the same reading if the tests are replicated, no matter how many times you measure something. There may be insiginificant margin of error. Some readings may differ by just a fraction but not large margins (Trochim, 2002). To ensure reliability and validity of the experiments, all the laboratory apparatus were calibrated before use by checking the apparatus measurements with other opperatus and the readings were the same First series of experiments using clean water were conducted under (dry run) followed by a series of similar tests. A dry run is the first experiment conducted during a series of similar test to be conducted. Several replicate tests were done and the results recorded were consistent as recorded on sheets attached to appendix A.

CHAPTER 4: RESULTS, DISCUSSION AND ANALYSIS

4.1 Introduction

Both the field and laboratory results are discussed and analysed in this chapter. The field data results focus on the existing road network in the study area in relation to housing development and how that would influnce the effectiveness and sustainability of a pervious pavement. The results are for a sample of roads only and the analysis is on how the roads' width, length, terrain and proximity to the houses would affect the performance of a pervious pavement.

The laboratory results analysis compares filtration effectiveness of each type of pervious pavement both with clean water and silt/sand contiminated water. Silt/sand contaminated water was used to simulate storm water and measured how effective filtration was for each pervious pavement type. The results obtained were compared, to establish which pervious pavement type produced the most effective filtration rate both with clean and silt/sand contaminated water.

In determining the suitable pervious pavement for township development, both field and laboratory results were taken into consideration.

4.2 Field results

4.2.1 Street width, length and terrain

A total of 30 randomly selected streets were measured. The results obtained are displayed in Table 4.1. The results reveal that:

i. The maximum street width is 6m wide with the smallest being 4m wide. The smallest street is 4m wide, which is in line with Guildlines on the Planning and Design of Township roads and storm water drainage manual (1981) published by SAICE. The shortest street is 200m and the longest 3.0km. All the streets are interconnected and sloping towards the lowest area of the whole township which is the stream along the wetland.

ii. From a total of 30 streets measured, only 5 streets have flat terrain which constitues 16.6% of the total measured streets. Balnace of 25 which consitutes of 83.4% have gentle rolling to steep rolling slopes which is one of the factors to be critically considered in pervious pavement design for it to be effective. Lindow, Smith & Eisenberg (2015) state that the design of permeable pavements on slopes if the storm water is required to drain into the sub-grade material, requires special considerations to prevent concetration of drained storm water downstream at the lower section of the pervious pavement. If the surface slope is too steep, there is need to incorporating subsurface terracing, check-dams, baffles, partitions, berms, or some combination to inhibit lateral flow and promote vertical infiltration.

In this study, pervious pavements are intergrated with detention ponds. The detention ponds will be located on open spaces available as discussed in Sub-section 4.2.3. The storm water collected in the base layer (reservoir) is collected through pipes by gravitational flow to the detention ponds situated at the lowest point of the streets. Therefore, slopping terrain in this case is necessary.

iii. Retrofiting of pervious pavements on existing streets is possible. However, the retrofiting costs are high and it may be an expensive exercise for developing countries such as South Africa. The existing asphalt surfaced roads in study area Diepsloot Township will not be retrofited. The existing gravel streets can be upgraded to permeable interlocking pavers. Equally, for new developments, permeable interlocking pavers can be used for road/street network.

TABLE 4.1: Street dimensions, surfacing and slope

Street No.	Width (m)	Length (m)	Surfacing	Terrain
1	5	900	Paved AS	Rolling
2	5	300	Paved As	Gentle to steep
3	5	1 200	Paved AS	Rolling
4	5	300	Paved AS	Rolling
5	5	200	Paved AS	Gentle
6	6	2 800	Paved AS	Gentle to steep
7	5	400	Paved AS	Rolling
8	5	400	Paved AS	Rolling
9	5	300	Paved AS	Gentle rolling
10	5	250	Paved AS	Gentle rolling
11	4	200	Gravel	Flat
12	4	800	Gravel	Gentle rolling
13	4	200	Gravel	Flat
14	6	1 200	Paved AS	Gentle rolling
15	6	1 000	Paved AS	Gentle rolling
16	5	200	Paved AS	Flat
17	5	200	Paved AS	Flat
18	5	200	Paved AS	Gentle rolling

19	5	200	Paved AS	Gentle rolling
20	5	250	Paved AS	Gentle rolling
21	6	1 000	Paved AS	Rolling
22	5	250	Paved AS	Rolling
23	5	200	Paved AS	Flat
24	5	200	Paved AS	Rolling
25	5	300	Paved AS	Gentle rolling
26	5	250	Paved AS	Gentle rolling
27	5	280	Paved AS	Gentle rolling
28	6	3 000	Paved AS	Rolling
28	5	400	Paved AS	Gentle rolling
30	5	200	Paved AS	Gentle rolling
Average	**5m**	**379.3m**	**Paved AS**	**Generally sloping**

The slopping streets and open spaces at the lowest points of the study area make the integrated pervious pavements with land use by combining the system with detention ponds viable. Hence slope as a design factor was considered (Lindow, Smith & Eisenberg, 2015). Therefore, it is necessary to establish the slopes of the streets/area where pervious pavements installation is proposed. Taking the average length and width of 379.3m x 5m respectively and applying 0.3m base thickness, the total volume of the base is 568.95m^3. Applying a void ratio of 23% which is the average from data in Table 2.1; chapter 2, 130.85m^3 of voids to be filled by storm water per street.

The majority of the roads (83.34%) in the study area have gentle rolling to rolling slopes as presented in Table 4.2. These slopes are suitable where storm water harvesting is intended for other uses like in this study. The other critical factors are; street width and its length which are required when determining the base layer (reservoir) thickness. The average width and length of streets obtained in Table 4.2 are necessary when designing a pervious pavement suitable for a township development. In the study area, most streets are paved with asphalt. This shouldn't be a problem in installation of pervious pavement because it is possible to retro fit pervious pavements.

4.2.2 Distance between the street edge and houses.

The results for measured distance between the street edge and houses are presented in Table 4.2.

TABLE 4.2: Distance between the street edge and houses

Street No.	Length between houses and street (m)	Street No.	Length between houses and street (m)
1	3	16	3
2	3	17	3
3	3.5	18	4
4	4	19	3.5
5	4	20	4
6	4	21	4
7	3	22	4
8	4	23	4
9	4	24	4
10	3.5	25	4
11	3	26	4
12	3.5	27	3.5
13	3	28	4
14	5	29	4
15	4	30	4
Average	**3.63m**		**3.8m**
Overall average (3.63 + 3.8)/2		**=**	**3.72m**

The results reveal that the houses are very close to the street edges with an average distance of 3.72m. Based on these results it is suggest that there is a lot of human activities spealing into the streets because there is not much space between the houses and the streets. These activities including the pedestrains walking along the sides increase the generation of sand and silt which can clogg pervious pavements.

Sand and silt have an impact on the performance of the pervious pavement because the main factor affecting pervious pavements performance is clogging (Zhang *et al.,* 2018; Chopra *et al.,* 2011). Furthermore, the un-intended litter and debris deposits on the streets can cause clogging of pervious pavements. Therefore, in determining the suitable pervious pavement selection for township developement this factor was taken into consideration.

4.2.3 Size of available land and distance from the clossest street(s).

The large open spaces along the stream and isolated small open spaces in between houses are required for installation of detention ponds. The open spaces sizes were not measured due to accessibility hindered by overgrown vegetation (reeds) and in some cases denied by local residents who use some of the open spaces for social gatherings. However, from visual estimates, the open spaces along the stream are large to accommodate a string of detention ponds each with a capacity of not less than 1 500m^3, and still remain with enough space for agricultural ultilistation, such as vegetable gardens. The isolated smaller open spaces located at the lowest point of streets can be used as local detention ponds. Therefore, it is posible to harvest storm water from the pervious pavement and channel it to the detention ponds by gravity flow through pipe network.

4.3 Laboratory experimental results

The results of the laboratory experiments are presented for two categories. The results of the first set of experiments were drawn from the filtration tests done using clean water. The second set of experiments were derived from filtration tests using contaminated water (clogging test). Thereafter, the two sets of results are compared in order to determine the net decrease in filtration of each pervious pavement sample. Hence, to determine the suitable pervious pavement for township development, taking into account field results from Table 4.1 and Table 4.2 as well.

4.3.1 Filtration rate using clean water

4.3.1.1 Filtration rate results

The volume of water filtered per fixed time period of 200 seconds for each pervious pavement test conducted was calculated from the measured drop in water level. The results are of measured drop in water level are recoded in Table 4.3.

TABLE 4.3: Filtration with clean water

Test No.	Time period for test (s)	Water level at start of test (mm)	Water level at end of test (mm)	Drop in water level (mm)	Water level at end of test (mm)	Drop in water level (mm)	Water level at end of test (mm)	Drop in water level (mm)
			Pervious Interlocking pavers		Pervious concrete		Pervious asphalt	
1	200	60	278	218	193	133	284	224
2	200	60	278	218	193	133	284	224
3	200	60	275	215	190	130	290	230
4	200	60	277	217	190	130	290	230
5	200	60	277	217	185	125	290	230
6	200	60	277	217	185	125	290	230
7	200	60	276	216	185	125	290	230
8	200	60	276	216	185	125	290	230
9	200	60	276	216	185	125	290	230
10	200	60	276	216	170	110	290	230
11	200	60	277	217	168	108	290	230
12	200	60	276	216	168	108	290	230
13	200	60	276	216	170	110	290	230
14	200	60	276	216	170	110	290	230
15	200	60	277	217	169	109	290	230
16	200	60	276	216	170	110	290	230

The volume of filtered water for each test was calculated using data in table 4.3. For each test conducted, the volume (v) of water was calculated as follows;

V = Surface area of the test container ($0.245m^2$) x drop in water level (m)

V = $0.245m^2$ x 0.218m

V = $0.0534\ m^3$ (recorded in table 4.4 as the filtered volume of water for the 1st interlocking pavers test)

The same calculation was used for tests to get the filtered volume of water and recorded in Table 4.4. The filtration rates recorded in Table 4.4 were calculated using formula 1 ($Q = V/t$) in sub-section 3.2.2.1. The calculation for each test was as follows:

- $Q = \dfrac{V}{t}$
- $Q = \dfrac{V}{200}$
- $Q = \dfrac{0.0534\ m^3}{200\ s}$

  $= 0.000267 m^3/s$

The filtration rate results 'Q' in m^3/s presented in Table 4.4 were converted to *l/s* by multiplying each value by $100l/m^3$ and the results are recorded in Table 4.5.

TABLE 4.4: Filtration volume in m^3

Test No.	Time period for test (s)	Drop in water level (m)	Filtered water volume (m^3)	Filtration rate (m^3/s)	Drop in water level (m)	Filtered water volume (m^3)	Filtration rate (m^3/s)	Drop in water level (m)	Filtered water volume (m^3)	Filtration rate (m^3/s)
		Pervious Interlocking pavers			Pervious concrete			Pervious asphalt		
1	200	0.218	0.0534	0.000267	0.133	0.0326	0.000163	0.224	0.0549	0.000275
2	200	0.218	0.0534	0.000267	0.133	0.0326	0.000163	0.224	0.0549	0.000275
3	200	0.215	0.0527	0.000264	0.130	0.0319	0.000159	0.230	0.0564	0.000282
4	200	0.217	0.0532	0.000266	0.130	0.0319	0.000159	0.230	0.0564	0.000282
5	200	0.217	0.0532	0.000266	0.125	0.0306	0.000153	0.230	0.0564	0.000282
6	200	0.217	0.0532	0.000266	0.125	0.0306	0.000153	0.230	0.0564	0.000282
7	200	0.216	0.0529	0.000265	0.125	0.0306	0.000153	0.230	0.0564	0.000282
8	200	0.216	0.0529	0.000265	0.125	0.0306	0.000153	0.230	0.0564	0.000282
9	200	0.216	0.0529	0.000265	0.125	0.0306	0.000153	0.230	0.0564	0.000282
10	200	0.216	0.0529	0.000265	0.110	0.0269	0.000135	0.230	0.0564	0.000282
11	200	0.217	0.0532	0.000266	0.108	0.0265	0.000133	0.230	0.0564	0.000282
12	200	0.216	0.0529	0.000265	0.108	0.0265	0.000133	0.230	0.0564	0.000282
13	200	0.216	0.0529	0.000265	0.110	0.0269	0.000135	0.230	0.0564	0.000282
14	200	0.216	0.0529	0.000265	0.110	0.0269	0.000135	0.230	0.0564	0.000282
15	200	0.217	0.0532	0.000266	0.109	0.0267	0.000134	0.230	0.0564	0.000282
16	200	0.216	0.0529	0.000265	0.110	0.0267	0.000134	0.230	0.0564	0.000282

TABLE 4.5: Filtration rates in *l/s*

Test No.	Filtration rate (*l*/s)	Filtration rate (*l*/s)	Filtration rate (*l*/s)
	Pervious Interlocking pavers	**Pervious concrete**	**Pervious asphalt**
1	0.267	0.163	0.275
2	0.267	0.163	0.275
3	0.264	0.159	0.282
4	0.266	0.159	0.282
5	0.266	0.153	0.282
6	0.266	0.153	0.282
7	0.265	0.153	0.282
8	0.265	0.153	0.282
9	0.265	0.153	0.282
10	0.265	0.135	0.282
11	0.266	0.133	0.282
12	0.265	0.133	0.282
13	0.265	0.135	0.282
14	0.265	0.135	0.282
15	0.266	0.134	0.282
16	0.265	0.134	0.282
Average	**0.265**	**0.145**	**0.282**

It can be observed that the initianal filtration rate and last filtration rate for pervious concrete vary maginally. This could be atributed to chemical reactions within the pervious concrete pavement when it was submerged in water. The graphical presentation of filtration rates presented in Table 4.5 is shown on Figure 4.1 and 4.2.

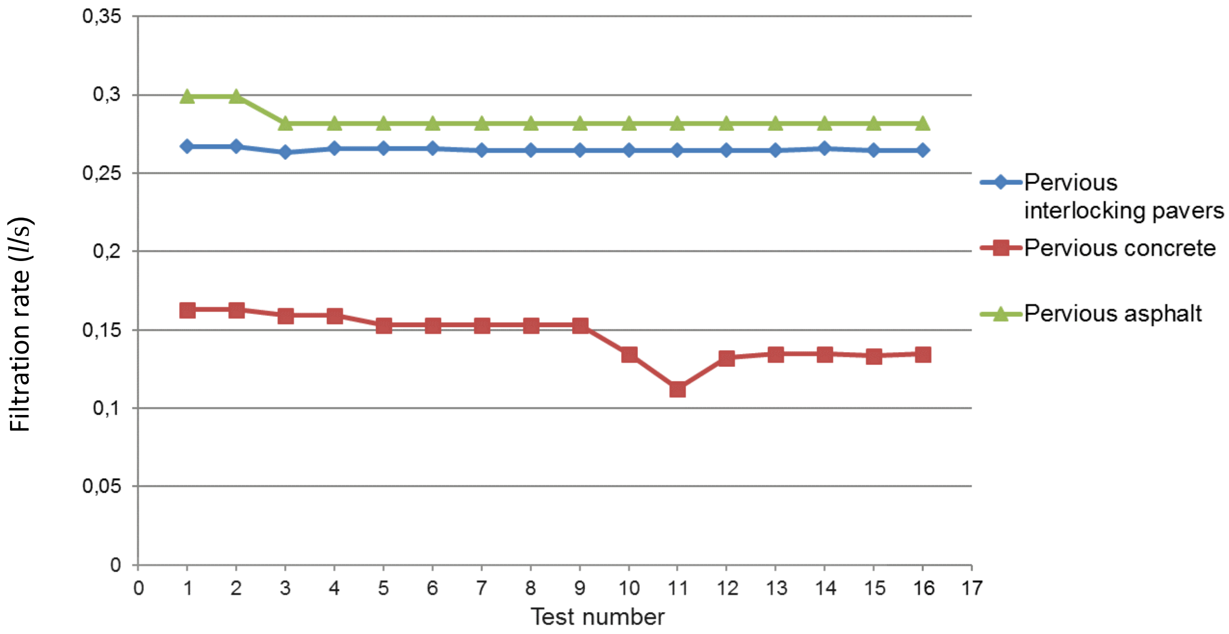

FIGURE 4.1: Filtration rates with clean water graph

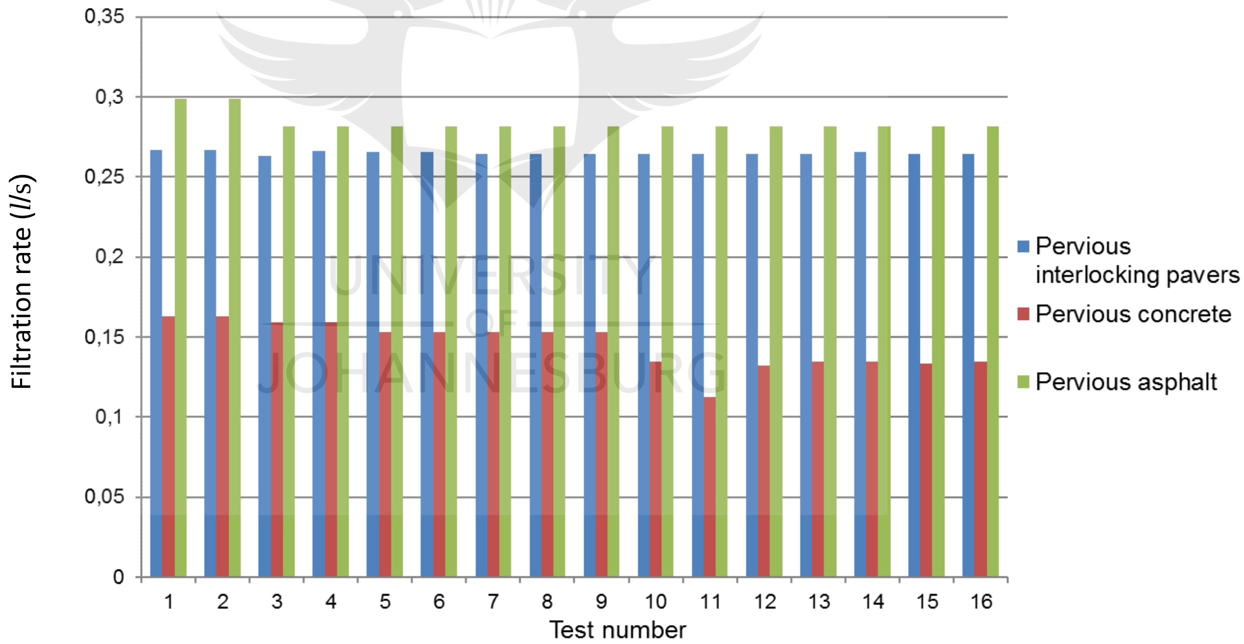

FIGURE 4.2: Filtration rates with clean water bar chart

4.3.1.2 Filtration rate using clean water results analysis

Pervious asphalt recorded the highest filtration rate with an average of 0.282 *l/s* followed by pervious interlocking pavers with 0.265 *l/s*. Pervious concrete recorded the lowest filtration rate with an average of 0.145 *l/s*. However, all three pervious pavement samples showed consistence in terms of the filtration rate per test conducted, though concrete slightly dropped on the last 3 tests. The reason was not investigated and it could be attributed to many factors. One of the factors could be due to chemical reaction within the pervious concrete affecting the effective void ratio.

Based on these filtration rates, and assuming all other factors except for variation in thicknesses of pervious pavement samples, to be constant, pervious asphalt pervious pavement would allow more water through, than the other two pervious pavements. However, there are many other factors to be considered when deciding and designing a pervious pavement to manage storm water run-off. One of the factors to be considered is clogging, because storm water runoff carries a lot of debris, sand and silt which can clog the voids of the pervious pavement.

4.3.2 Filtration rate using contaminated water (clogging test)

Every after each filtration test done, the filtered water containers were checked for clogging material (sand and silt) having filtered through the test samples. There was very little and in some cases no evidence of accumulation of clogging material. Instead, the large quantities of clogging material accumulated on the surfaces of the test samples, as it is indicated on Figures 4.3. Based on these observation, it can be concluded that clogging happens between 0mm to 30mm of the pervious pavement surface while the underneath layer beyond the 30mm clogging is almost zero (Chopra *et al.,* 2011; Zhang *et al.,* 2018 & Yong *et al.,* 2013).

Silt material on the surface of the pervious sample

FIGURE 4.3: Clogging material (silt) on the surfaces

4.3.2.1 Filtration rate using sand as contaminant

The volume of water filtered per fixed time period of 200 seconds for each pervious pavement test conducted was calculated just like in sub-section 4.3.1 (fitration rate using clean water). Table 4.6 contains the tests data used to calculate the filtration rates.

TABLE 4.6: Filtration with sand as contaminat (Clogging test)

Test No.	Time period for test (s)	Water level at start of test (mm)	Water level at end of test (mm)	Drop in water level (mm)	Water level at end of test (mm)	Drop in water level (mm)	Water level at end of test (mm)	Drop in water level (mm)
			Pervious interlocking pavers		Pervious concrete		Pervious asphalt	
1	200	60	260	200	160	100	290	230
2	200	60	215	155	145	85	280	220
3	200	60	215	155	142	83	270	210
4	200	60	210	150	142	82	270	210
5	200	60	210	150	140	80	270	210
6	200	60	210	150	140	80	265	215

The filtration rates were calculated in a similar manner as in sub-section 4.3.1 (Filtration rate using clean water). The data used for the calculation is from Table 4.6. The filtration results ‘Q’ in m^3/s and in *l*/s are recorded in Table 4.7 and Table 4.8, respectively.

TABLE 4.7: Filtration volume m^3 with sand as contaminant

Test No.	Time period for test (s)	Drop in water level (m)	Filtered water volume (m^3)	Filtration rate (m^3/s)	Drop in water level (m)	Filtered water volume (m^3)	Filtration rate (m^3/s)	Drop in water level (m)	Filtered water volume (m^3)	Filtration rate (m^3/s)
		Pervious interlocking pavers			Pervious concrete			Pervious asphalt		
1	200	0.200	0.049	0.000245	0.100	0.0245	0.000123	0.230	0.05635	0.000282
2	200	0.155	0.038	0.000189	0.085	0.0208	0.000104	0.220	0.05390	0.000269
3	200	0.155	0.038	0.000189	0.083	0.0203	0.000102	0.210	0.05145	0.000257
4	200	0.150	0.037	0.000184	0.082	0.0201	0.000101	0.210	0.05145	0.000275
5	200	0.150	0.037	0.000184	0.080	0.0196	0.000098	0.210	0.05145	0.000275
6	200	0.150	0.037	0.000184	0.080	0.0196	0.000098	0.215	0.05268	0.000263

TABLE 4.8: Filtration rates in *l/s* with sand as contaminant

Test No.	Filtration rate (l/s)	Filtration rate (l/s)	Filtration rate (l/s)
	Pervious interlocking pavers	Pervious concrete	Pervious asphalt
1	0.245	0.123	0.282
2	0.189	0.104	0.269
3	0.189	0.102	0.257
4	0.184	0.101	0.275
5	0.184	0.098	0.275
6	0.184	0.098	0.263
Average	**0.194**	**0.104**	**0.263**

The graphical presentation of filtration rates presented in Table 4.8 is shown on Figures 4.5 and 4.6.

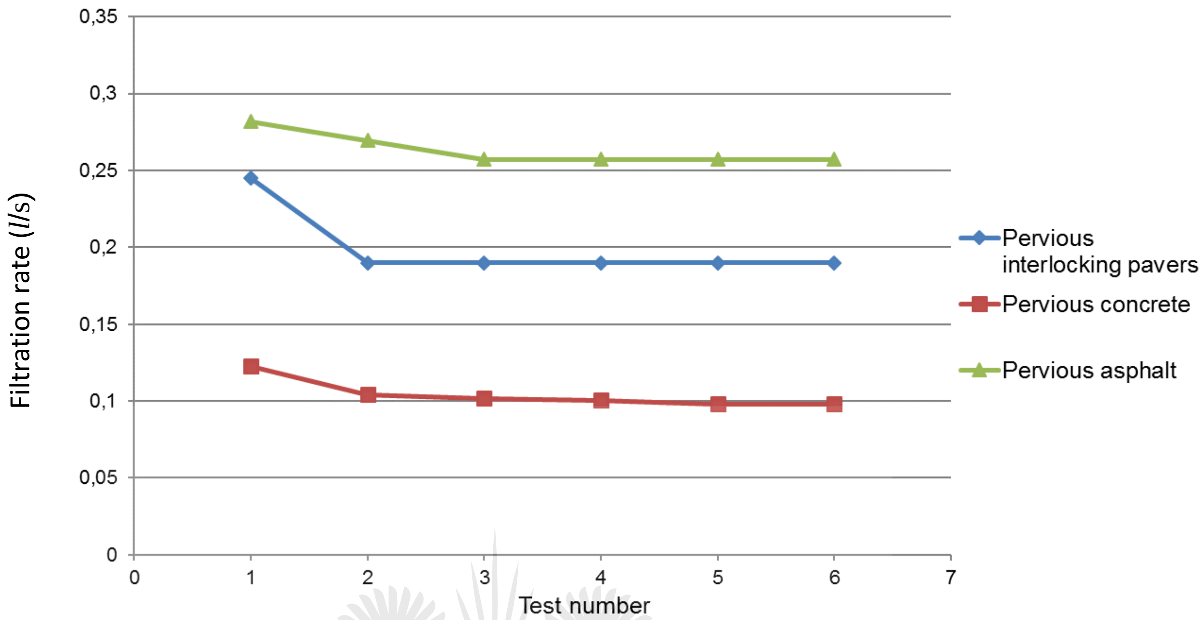

FIGURE 4.5: Filtration rates with sand contaminated water graph

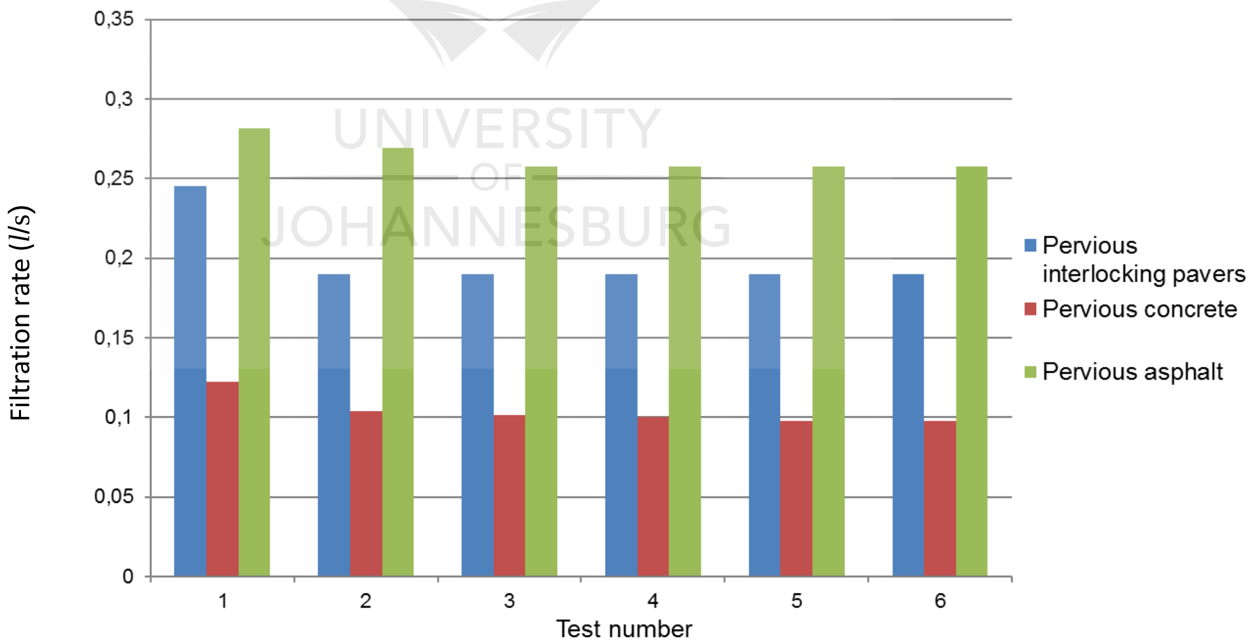

FIGURE 4.6: Filtration rates with sand contaminated water bar chart

4.3.2.2 Filtration rate results using silt as contaminant

The volume of water filtered per fixed time period for each pervious pavement test conducted was calculated in the same manner as in sub-section 4.3.1 (fitration rate using clean water). Table 4.9 contains the tests data used to calculate the filtration rates.

TABLE 4.9: Filtration with silt as contaminat (Clogging test)

Test No.	Time period for test (s)	Water level at start of test (mm)	Water level at end of test (mm)	Drop in water level (mm)	Water level at end of test (mm)	Drop in water level (mm)	Water level at end of test (mm)	Drop in water level (mm)
			Pervious interlocking pavers		Pervious concrete		Pervious asphalt	
1	200	60	207	147	135	75	280	220
2	200	60	207	147	130	70	260	200
3	200	60	199	139	126	66	260	200
4	200	60	215	155	125	65	253	193
5	200	60	213	153	116	56	250	190
6	200	60	187	127	115	55	250	190

The filtration rates were calculated in a similar manner as in sub-section 4.3.1 (Filtration rate using clean water). The data used for the calculation is from Table 4.9. The filtration results ‘Q’ in m^3/s and in *l*/s are recorded in Table 4.10 and Table 4.11, respectively.

TABLE 4.10: Filtration volume in m^3 with silt as contaminant

Test No.	Time period for test (s)	Drop in water level (m)	Filtered water volume (m^3)	Filtration rate (m^3/s)	Drop in water level (m)	Filtered water volume (m^3)	Filtration rate (m^3/s)	Drop in water level (m)	Filtered water volume (m^3)	Filtration rate (m^3/s)
		Pervious interlocking pavers			Pervious concrete			Pervious asphalt		
1	200	0.147	0.0360	0.000180	0.075	0.018375	0.000092	0.220	0.0539	0.000269
2	200	0.147	0.0360	0.000180	0.070	0.017150	0.000086	0.200	0.0490	0.000245
3	200	0.139	0.0340	0.000170	0.066	0.016170	0.000081	0.200	0.0490	0.000245
4	200	0.155	0.0134	0.000067	0.065	0.015925	0.000079	0.193	0.0473	0.000237
5	200	0.153	0.0130	0.000065	0.056	0.013720	0.000067	0.190	0.0466	0.000233
6	200	0.126	0.0310	0.000155	0.055	0.013475	0.000067	0.190	0.0466	0.000233

TABLE 4.11: Filtration rates in *l/s* with silt as contaminant

Test No.	Filtration rate (*l*/s)	Filtration rate (*l*/s)	Filtration rate (*l*/s)
	Pervious interlocking pavers	Pervious concrete	Pervious asphalt
1	0.180	0.092	0.269
2	0.180	0.086	0.245
3	0.170	0.081	0.245
4	0.067	0.079	0.237
5	0.065	0.067	0.233
6	0.155	0.067	0.233
Average	**0.169**	**0.079**	**0.244**

The graphical presentation of filtration rates presented in Table 4.11 is shown on Figures 4.7 and 4.8.

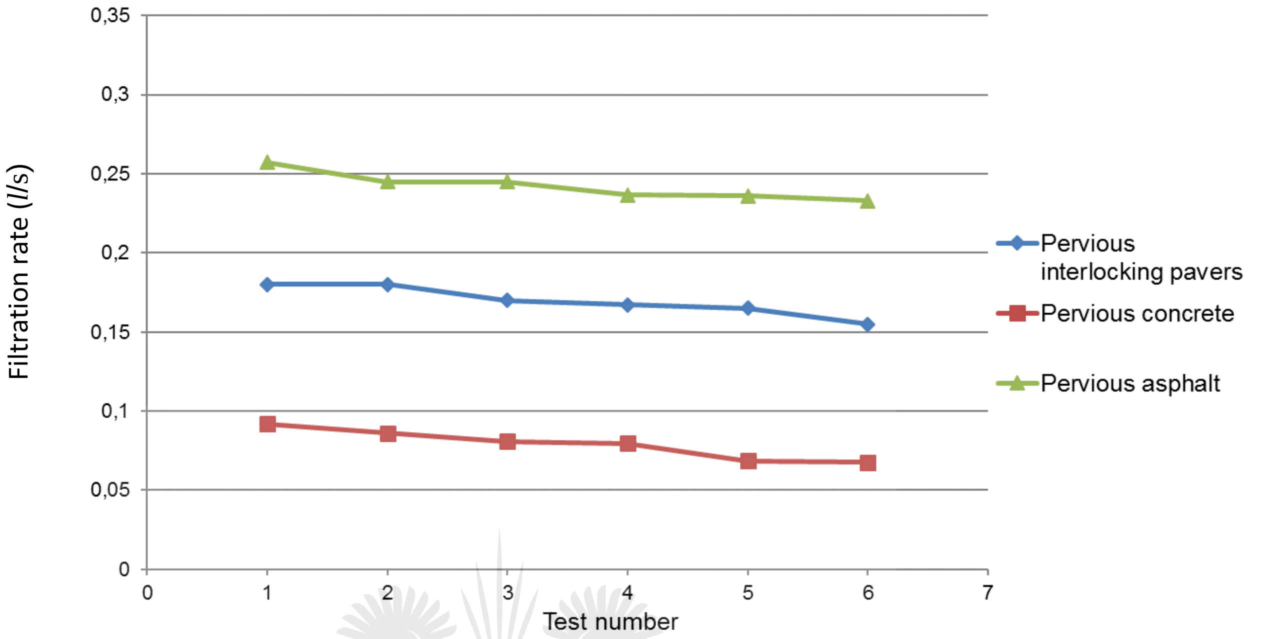

FIGURE 4.7: Filtration rates with silt contaminated water graph

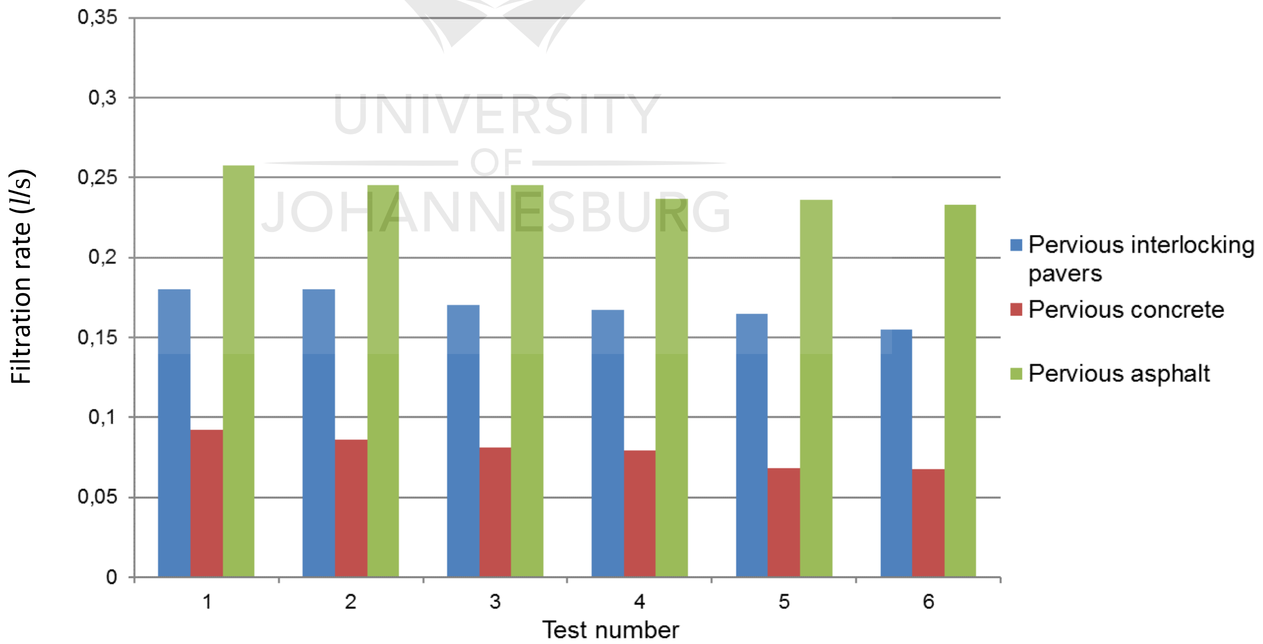

FIGURE 4.8: Filtration rates with silt contaminated water bar chart

The filtration results using 0.5mm single graded sand and silt from study area presented in Table 4.8 and Table 4.11 respectively were plotted on a single graph and is shown on Figures 4.9 and 4. 10.

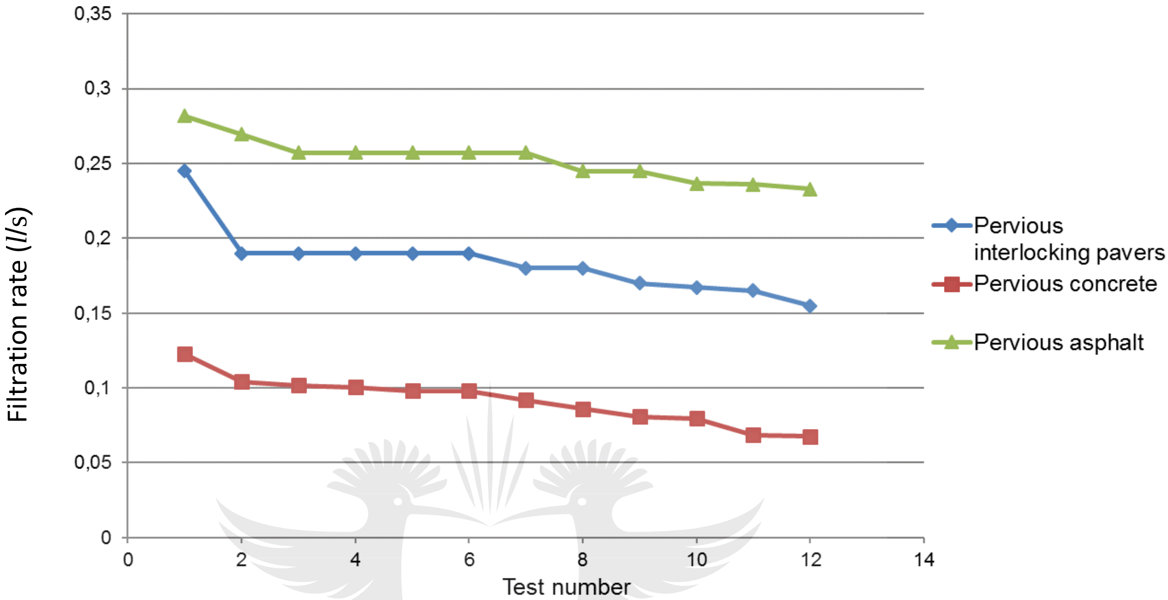

FIGURE 4.9: Combined clogging test graph

It can be seen from the graph that the filtration rates for all three test samples were dropping. This is an indication that clogging hinders filtration rate over a period of time.

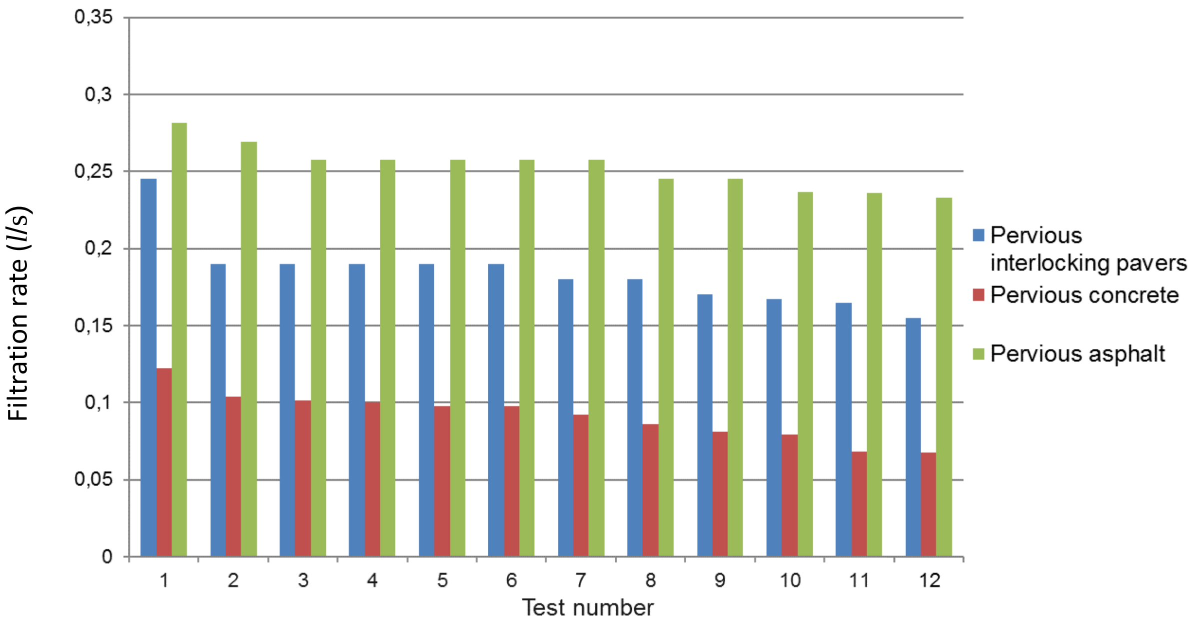

FIGURE 4.10: Combined clogging test bar chart

In conclusion of the clogging test, the presences of sediments did affect the filtration to a certain degree on all pervious pavements but did not reduce filtration rate to almost 0%. Therefore, it can be concluded that all pervious pavements are capable of intercepting sediments though the degree of intercepting which reduces the infiltration rate varies and it affects the filtration rate efficiency.

The filttration efficience of each pervious pavements when loaded with silt and sand poluted water was checked by calculating the percentage reduction in filtration rate. The calculated filtration reduction results are as follows:

i. Interlocking pavers

Percentage drop = $\left(\frac{\text{Initial filtration} - \text{Final filtration}}{\text{Initial filtration}}\right) \text{x}100\%$

$$= \left(\frac{0.245l/\text{s} - 0.155l/\text{s}}{0.245\text{Lt/s}}\right) \text{x}100\% \quad = \mathbf{36.73}\%$$

ii. Pavervious concrete

Percentage drop = $\left(\frac{\text{Initial filtration} - \text{Final filtration}}{\text{Initial filtration rate}}\right) \text{x}100\%$

$$= \left(\frac{0.123l/\text{s} - 0.067l/\text{s}}{0.123\text{Lt/s}}\right) \text{x}100\% \quad = \mathbf{45.52}\%$$

iii. Pervious asphalt

Percentage drop = $\left(\frac{\text{Initial filtration} - \text{Final filtration}}{\text{Initial filtration rate}}\right) \text{x}100\%$

$$= \left(\frac{0.282l/\text{s} - 0.233l/\text{s}}{0.282\text{Lt/s}}\right) \text{x}100\% \quad = \mathbf{17.38}\%$$

4.3.2.3 Filtration results of sand and silt contaminated water analysis

These results represent the behavior of the three pervious samples in terms of clogging. The pervious asphalt pavement sample produced highest filtration rates in all tests followed by pervious interlocking pavers. The pervious concrete recorded the lowest fitration rate. Comparing the three pervious samples interms of the reduction in filtration rate caused by clogging, pervious concrete recorded the highest reduction of 45.52% followed by pervious interlocking pavers with 36.73%. Pervious asphalt recorded the lowest filtration rate reduction of 17.38%.

4.3.3 Results analysis

The filtration rates results show that all pervious samples produced relatively good filtration rates with clean water. The difference in thickness of pervious samples with maximum difference of 60mm, which was between pervious asphalt and pervious concrtete, was not taken as a major factor in the analysis of results. The reason being the same surface area for pervious samples used was considered to be relatively small to have a major effect on water head pressure to largely affect the filtration rates. Pervious asphalt recorded highest average filtration rate followed by pervious interlocking pavers. Pervious concrete recorded the lowest. When subjected to clogging test, the filtration rates for all samples steadily reduced. Of all three samples, pervious asphalt recored the lowest filtrate rate reduction of 17.33% follwed by pervious interlocking pavers with 36.73%. Pervious concrete recorded the highest reduction of 45.52%. The filtration reduction margins between pervious asphalt and pervious interlocking pavers is 19,33% compared to the margin between pervious interlocking pavers and pervious concrete, which is 8.79%, while the reduction in margin between pervious asphalt and pervious concrete is 28.19%.

Clogging is a major factor in pervious pavements. The effectiveness of pervious pavement in terms of filtration was affected over a series of tests done. The results show that the filtration rates decline over a series of tests. This confirms previous research that clogging is a major hinderance factor in terms of pervious pavement sustainability. Maintenance plans must be in place to mitigate clogging problem. Based on these results, pervious asphalt pavement would behave favourably in terms of storm water management followed by pervious interlocking pavers and pervious concrete last.

4.4 Concluding remarks

The close proximity of households in study area can contribute to silt generation which contaminates storm water during storm and silt gets spilled/brown into the streets during dry season. Silt is generated due to human activities around the households and walk ways. Having open spaces, especially on the lower sides of the streets provide space for construction of detention ponds receiving storm water from pervious pavements. Furthermore, the streets have adequate slope suitable for gravitational flow of harvested storm water through pipe network to the detention ponds.

The laboratory test results show that pervious asphalt has more filtration capacity than the other two pervious pavements for storm water management. However, there are other social economic factors to be considered which will influence the choice for the type of pervious pavement suitable for the study area.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1 Overview

The broad objective of this study was to investigation through field research and laboratory tests which type of pervious pavement is more suitable for township development to effectively reduce storm water runoff and peak flow flooding. Townships in South Africa experience devastating floods which cause serious damage to municipal infrastructure, shelter and in some cases loss of life. To mitigate or prevent devastating peak flow floods, there was a need to investigate a the suitable pervious pavement type that can be used in township development because pervious pavements significantly reduce peak flow flooding.

5.2 Conclusion

5.2.1 Factors considered in deciding a suitable pervious pavement

Three critical factors were considered in this study in deciding the suitable pervious pavement in township development. These are as folows:

i. Existing local conditions of townships which include shelters proximity to roads/streets.
ii. Social economic challenges which exist in a township.
iii. Filtration rates of the three pervious pavement samples tested.

5.2.1.1 Existing local conditions

Pervious pavements operate on the principle of having effective interconnected voids in the pavement structure to allow filtration of storm water. Thus, they are sensitive to clogging. The local conditions namely; close proximity of houses to streets, street slope, and community activities must be considered because they directly or indirectly contribute to clogging sand and silt. These affects the operations and maintenance plan of the selected choice of the pervious pavement so that it is effective and sustainable. The other factor considered is available land required for detention ponds .

The sloping streets and availability land for detention ponds are favourable for pervious pavement installation integrated with detention ponds. The close proximity of houses to the streets and community activities which contribute to sand and silt into the streets are other factors which were critically considered in arriving at a suitable pervious pavement type for township development.

5.2.1.2 Social Economic challenges

Densely populated developments which include townships have major social economic challenges. One of the challenges is high un-employment rate and lack of recreation facilities which. These challenges can be addressed by creating employment opportunities and recreation facilities. This study investigated the suitable pervious pavement for township installation intergrating it with land use by installation of detention ponds. These detention ponds can be used as recreation facilities and also provide irrigation water for community vegetable gardens to uplift their economic status once the Local Government Authorities have been consulted and authorised for community based small scale vegetable farming through co-operatives.

The pervious pavement recommended to be suitable should be able to generate employment opportunities during construction and post construction through maintenace.

5.2.1.3 Filtration rates

As indicated in sub-section 5.2.1.1, pervious pavements work on a principle of allowing storm water to infiltrate through. Once infitration is hindered, the pervious pavement will stop being effective. Therefore, the pervious pavement with high infiltration rate is more effective in any installation. The laboratory infiltration rate test results using clean water show that pervious asphalt pavement sample was more effective with an average infiltration rate of 0.282 *l*/s followed by pervious interlocking pavers with 0.265 *l/s*. Pervious concrete was last with 0.145 *l/s*.

From the twelve replicate laboratory clogging tests done, pervious asphalt was more effective with less infiltration rate reduction having reduced by 17.38% followed by pervious interlocking pavers having reduced by 36.73%. Pervious concrete was the worst with 45.52%

reduction in infiltration rate. This is critical because clogging in pervious pavements performance is the most serious drawback.

5.2.2 Pervious pavement suitable for township development

Based on the research results and considering the factors discussed in sub-section 5.2.1, Pervious interlocking pavers are more suitable. Figure A1(a) and A1(b) on appendix shows typical installation cross section and layout plan. The reasons for pervious interlocking pavers being more suitable are as follows:

a) Social economic reasons

- The interlocking pavers would generate more employment opportunities than pervious asphalt during construction period and post construction through maintenance programmes. This is so because, laying pervious interlocing pavers is more labour intensive than laying pervious asphalt which is machine based activity. During maintenance to remove clogging particles, more labour can be use to remove and clean the 7mm aggregate in between the pervious interlocking pavers whilst when cleaning pervious asphalt, a vacume machine is required.
- When more employment opportunities are generated during construction stage and during operations and maintenance period, people earn an income which improves their economic status reducing un-employment rate.

b) Performance reasons

- Pervious asphalt has an advantage over pervious interlocking pavers of 0.017 *l/s* in terms of infiltration rates with clean water and a difference of 19.35% between the two for clogging test reduction. The pervious interlocking pavers infiltration rates are able to reduce storm water peak flow flooding.
- Maintenance of pervious interlocking pavers is easier than pervious asphalt. If there is a problem on the base layer (reservoir layer), simply remove the pervious interlocking pavers and repair the base layer, then re-install removed pervious interlocking pavers. As for pervious asphalt, once asphalt is removed, it cannot be re-used unless recycled. New asphalt has to be delivered because it is not readily available within the township communities.

5.3 Recommendations

Determining the suitable pervious pavement for township development by investigating field and laboratory tests of the three different types of pervious pavements has been completed in this study. Further research is required as follows:

i. Further filtration rate tests on different type of pervious interlocking pavers with bigger gaps than the one used in this research.

ii. To develop a methodology that can be used to measure onsite subgrade infiltration rates where pervious pavement installation is proposed.

REFERENCES

Airport Cooperative Research Program (ACRP), (2017). *Research Report* 178. Guidance for Usage of Permeable Pavement at Airports [oline]. Available from https://www.nap.edu/catalog/24852/guidance-for-usage-of-permeable-pavement-at-airports (accessed 08/04/2019).

Ahn, J., Cho, W., Kim, T., Shin, H. and Heo, J. H. 2014. Flood Frequency Analysis for the Annual Peak Flows Simulated by an Event-Based Rainfall-Runoff Model in an Urban Drainage Basin. Journal of Water 6 (2014) 3841-3863.

Arndt, C., Davies, R. and Thurlow, J. 2018. Urbanization, structural transformation and rural-urban linkages in South Africa [online]. Available from https://csp.treasury.gov.za/Resource%20_Centre/Conferences/ Documents/Urbanization%20Review%20Papers/Paper%203%20-%20RSA%20Urbanization.pdf (accessed: 08/04/2019).

Barau, A. S. 2015. Perceptions and contributions of households towards sustainable urban green infrastructure in Malaysia. Journal of Harbat International 47(2015)285-297.

Bruinsma, J., Peshkin, D., Ballou, L., Eisenberg, B., Lurie, C., Costa, M., Ung, C., Nassiri, S., Shi, X. and Haselbach, L. 2017. Airport Cooperation Research Program (ACRP) Research Report 178. *Guidance for usage of Permeable Pavement at Airports. Chapter 2: Types of Permeable Pavements and their benefits.* The National Academies of Sciences, Engineering and Medice. 500 Fifth St., NW | Washington, DC 20001 [online]. Available from https://www.nap.edu/read/24852/chapter/4 (accessed: 26/06/2019).

Chopra, M., Stuart, E., Hardin M., Uju, I. and Wanielista, M. 2011. Storm water Management Academy University of Central Florida Orlando, FL 32816; *Pervious Pavements - Installation, Operations and Strength Part 1: Pervious*

Concrete Systems Final report [online]. Available on https://nacto.org/docs/usdg/pervious_pavements_installation_operations_and_strength_chopra.pdf (accessed on 3/04/2019).

Cobbinah, P. B., Erdiaw-kwasie, M. O. and Amoateng, P. 2015. Africa's urbanisation: *Implications for sustainable development*. Journal of Cities 47 92015) 62-72.

Cosic, K., Korat, L., Ducman, V. and Netinger, I. 2015. Influence of aggregate type and size on properties of pervious concrete. Journal of Construction and Building Materials 78(2015) 69-76.

Dalu, M. T. B., Shackleton, C. M. and Dalu, T. 2018. Influence of land cover, proximity to streams and household topographical location on flooding impact in informal settlements in the Eastern Cape, South Africa. International Journal of Disaster Risk Reduction 28 (2018) 481-490.

Department of Cooperative Governance and Traditional Affairs, 2018. Annual report 2017/18 Financial year [online]. Available from www.cogta.gov.za (accessed on 27/05/2018).

Department of Cooperative Governance and Traditional Affairs, 2017. Annual report 2016/17 Financial year [online]. Available from www.cogta.gov.za (accessed on 27/05/2018).

Department of Planning and Local Government, 2010, *Water Sensitive Urban Design Technical Manual for the Greater Adelaide Region,* Government of South Australia, Adelaide [online]. Available from https://www.sa.gov.au/__data/assets/pdf_file/0003/7770/WSUD_contents_and_glossary.pdf (accessed on 3/04/2019).

Department of Environmental Affairs and Tourism. Green Paper on an Environmental Policy for South Africa 1996 [online]. Available on https://www.environment.gov.za/legislation/greenpapers (accessed on 04/04/2019).

Dodman, D., Leck, H., Rusca, M. and Colenbrander, S. 2017. African Urbanisation and urbanism; *Implications for risk accumulation and reduction*. International Journal of Disaster risk reduction 26 920170 7-15.

Elshorbagy, A., Lindenas, K. and Azinfar, H. 2018. Risk-based quantification of the impact of climate change on storm water infrastructure. Journal of Water Science 32 (2018) 102–114.

Elmqvist, T., Setala, H., Handel, S. N., Van der Ploeg, S., Aronson, J., Blignaut, J. N., Gomez-Baggethun, E., Nowak, D. J., Kronenberg, J. and De Groot, R. 2015. Benefits of restoring ecosystem services in urban areas Journal of Environmental Sustainability [online]. Available on https://www.sciencedirect.com (accessed: 04/04/2019).

Furguson, B.K. 2006. Porous pavements: The making of progress in technology and design: 8th International Conference on Concrete Block Paving, November 6-8, 2006 San Francisco, California USA [online]. Available from http://www.sept.org/techpapers/1290.pdf (accessed on 11/04/2019)

Grubesa. I.N., Barisic, I., Ducman, V. and Korat, L. 2018. Draining capability of single-sized pervious concrete. Journal of Construction and Building Materials 169 (20180 252-260.

Hammes, G., Thives, L. P. and Ghisi, E. 2018. Application of storm water collected from porous asphalt pavements for non-potable uses in buildings. Journal of Environmental Management 222 (2018) 338 – 347.

Hong, Y. 2010. Experimental evaluation of design methods for in-site detention ponds. International journal of Sediment Research 25 (2010) 52-63.

Iavan, P. 2019. Heavy downpours, hail lead to flooding in Johannesburg [online]. Available from https://www.timeslive.co.za/news/south-africa/2019-03-06-heavy-downpours-hail-lead-to-flooding-in-johannesburg/ (accessed 12/04/2019)

Jamshidi, A., Kurumisawa, K., White, G., Nishizawa, T., Igarashi, T., Nawa, T. and Mao, J. 2019. State-of-the-art of interlocking concrete block pavement technology in Japan as a post-modern pavement. Journal of the Construction and Building Materials 200 (2019) 713-755

Johannesburg Roads Agency (JRA) Infrastructure Planning, 2010. Diepsloot stormwater master planning, by Civil Concepts (Pty) Ltd. 66 Pixely Seme Street (Previously Sauer Street), cnr. Rahima Moosa Street, Johannesburg.

Kamali, M., Delkash, M. and Tajrishy, M. 2017. Evaluation of permeable pavement response to urban surface runoff. Journal of Environmental Management 187 (2017) 43-53.

Kayhanian, M., li, H., Harvey, J. T. and Liang, X. 2019. Application of permeable pavements in highways for storm water runoff management and pollution prevention: California research experiences. International Journal of transportation science and technology (2019) [online]. Available from www.elservier.com/locate/ijtst (accessed on: 10/04/2019).

Kebler, S., Bierl, R., Meyer, B. and Klein, A. 2017. Chemical effects of a near-to-nature detention pond on a small urban headwater. Journal of Limnologica 62 92017) 118-125.

Koohmishi, M. and Shafabakhsh, G. 2018. Drainage potential of reservoir course of porous pavement for various particle size distributions of aggregate. Journal of Transportation Geotechnics 16 (20180 63 – 75.

Lindow, K. C., Smith, D. and Eisenberg, B. 2015. Permeable Pavements. American Society of Civil Engineering [online]. Retrieved from http://ebookcentral.proquest.com; created from ujlink-ebooks on 2019-04-01 05:55:52 (accessed on 3/04/2019).

Marlow, D.R, Moglia, M., Cook, S. and Beale, D.J. 2013. Towards sustainable urban water management: *A critical reassessment.* Journal of Water Research. 47(2013)7150-7161.

Mail & Guardian newspaper report, 2010. Heavy floods kill four people [online]. Available from https://mg.co.za/article/2010-01-26-heavy-floods-kill-four-people (accessed on: 11/04/2019).

Mersal, A. 2016. Sustainable Urban Future: Environmental Planning for sustainable urban development. Journal of Procedia Environmental Sciences 34 (2016) 49-61.

Miro, A., Hall, J., Rae, M. and O'Brien, D. 2018. Links between ecological and human wealth in drainage ponds in a fast-expanding city, and proposals for design and management. Jounal of Landscape and urban Planning (180 (2018) 93-102.

Miller, J. D. and Hutchins, M. 2017. The impacts of urbanisation and climate change on urban flooding and urban water quality: *A review of the evidence concerning the United Kingdom.* Journal of Hydrology: Regional Studies 12 (2017) 345-362.

Moghanddam, T. B., Karim, M. R. and Syammaun, T. 2012. Dynamic properties of stone mastic asphalt mixtures containing waste plastic bottles. Journal of Construction and Building Materials 34 (2012): 236-242.

Municipal Systems Act, 2000, Act 32 of 2000. Integrated Development Plan; Section 25 [online]. Available from http://www.tshwane.gov.za/sites/Council/

Ofiice-Of-The-Executive-Mayor/Pages/Integrated-Development-Planning.aspx (accessed on: 24/05/2019)

Preeti, J. and Dwarakish, G. S. 2015. Temporal analysis of spatial distribution of built-up area in Peri-urban areas of Cochin, Kerala: *Case study of sub-watershed in Periyar River.* Journal of Aquatic Procedia 4 (2015) 1445-1451.

Qin, Y., He, Y., Hiller, J. E. and Mei, G. 2018. A new water-retaining paver block for reducing runoff and cooling pavement. Journal of Cleaner Production 199 (2018) 948-956.

Ra'eesa, P. 2016. Mail and Guardian newspaper: *Still no shelter for Alex flood victims, foreign nationals search for lost documents* [online]. Available from https://mg.co.za/article/2016-11-10-still-no-shelter-for-alex-flood-victims-foreign-nationals-search-for-lost-documents (accessed: 08/04/2019)

Rahn, K. A., Davis, P. and Dougherty, M. 2017. Laboratory methods examining the effects of pavement runoff. Journal of Procedia Engineering 196 (2017) 527-534.

Razzaghmanesh, M. and Borst, M. 2019. Long term effects of permeable pavements on nutrient infiltration concentrations. Journal of Science of the Total Environment 670 (2019) 893-901.

Saadeh, S., Ralla, A., Al-Zubi, Y.m, Wu, R. and Harvey, J. 2019. Application of fully permeable pavements as a sustainable approach for mitigation of storm water runoff. International Journal of Transportation Science and Technology (2019). [online]. Available from www.elservier.com/locate/ijtst (accessed on: 10/04/2019).

Sasalone, J., Kuang, X., Ying, G. and Ranieri, V. 2012. Filtration and clogging of permeable pavement loaded by urban drainage. Journal of Water Research 46 (2012) 6763-6774.

Segaran, R. R., Lewis, M. and Ostendorf, B. 2014. Storm water quality improvement potential of an urbanised catchment using water sensitive retrofits into public parks. Journal of Urban Forestry & Urban Greening 13 (2014) 315–324.

Singh, P., Sinha, V. S. P., Vijhani, A. and Pahuja, N. 2018. Vulnerability assessment of urban road network from urban flood. International Journal of Disaster Risk Reduction 28 (2018) 237-250.

Statistics South Africa, 2019. National Poverty Lines 2019. [online]. Available from www.statssa.gov.za › publications › P031012019 (accessed on 10/10/2019).

Statistics South Africa, 2011. Natuional Census 2011. [online]. Available from www.statssa.gov.za › publication census (accessed on 10/10/2019).

Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter (2019). [online]. Available from https://www.astm.org/DATABASE.CART/HISTORICAL/D5084-03.htm (accessed on 10/08/2019).

Sun, Y., Pomeroy, C., Li, Q. and Xu, C. 2019. Impacts of rainfall and catchment characteristics on bioretention cell performance. Journal of Water Science and Engineering 12 (2019) 98-107.

South Africa weather service, 2019. Annual State of the Climate of South Africa. [online]. Available from https://www.weathersa.co.za/Documents/Corporate/Annual%20State%20of%20the%20Climate%202019.pdf (accessed on 10/08/2019)

Teye, J. 2018. United Nations expert group meeting for the review and appraisal of the programme of action of the international conference on population and development and its contribution to the follow-up and review of the 2030 agenda for sustainable development. *Report on Urbanization and migration in Africa* [online]. Available from https://www.un.org/en/ (accessed: 08/04/2019).

Tixier, G., Lafont, M., Grapentine, L., Rochfort, Q. and Marsalek, J. 2011. Ecological risk assessment of urban storm water ponds: *Literature review and proposal of new conceptual approach providing ecological quality goals and the associated bioassessment tools.* Journal of Ecological Indicators 1192011)1497-1506.

Trochim, W. M. K. 2002. Research Methods Knowledge base (online). Available from https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=14&cad=rja&uact=8&ved=2ahUKEwj82oKd6MjnAhUQlhQKHQ4wCzEQFjANegQIBBAB&url=https%3A%2F%2Fwww.researchgate.net%2Fpublication%2F243783609_The_Research_Methods_Knowledge_Base&usg=AOvVaw3Dwda1bzUnMa2UdNtolBXN [accessed 11/02/2020].

Vanstone Precast, (2019). 80mm Aqualock Pavers. (online). Available from http://www.vanstone.co.za/80mm_aqualock_pavers [accessed 10/05/2019].

Xie, N., Akin, M. and Shi, X. 2019. Permeable concrete pavements: A review of environmental benefits and durability. Journal of Cleaner Production 210 (2019) 1605-1621.

Yong, C. F., McCarthy, D. T. and Deletic, A. 2013. Predicting physical clogging of porous permeable pavements. Journal of Hydrology 481 (2013) 48-55.

Zeng, C., Song, Y., Cai, D., Hu, P., Cui, H., Yang, J. and Zhang, H. 2019. Exploration on spatial spill over effect of infrastructure network on urbanisation: *A case study in Wuhan urban agglomeration*. Journal of Sustainable Cities and Society 47 (2019) 1001476.

Zhang, J., She, R., Dai, Z., Ming, R., Ma, G., Cui, X. and Li, L. 2018. Experimental simulation study on pore clogging mechanism of porous pavement. Journal of Construction and Building Materials 187 (2018) 803-818.

Zhi, S., Gun, W. W., Hui, L. X. and Bo, T. 2012. Evaluation of fatigue crack behaviour in asphalt concrete pavements with different polymer modifiers. *Journal of construction and building materials,* 27 (2012): 117-125.

Zhong, R., Leng, Z. and Poon, C. 2018. Research and application of pervious concrete as a sustainable pavement material: *A state of-the-art and state-of-the-practice review*. Journal of Construction and Building Materials 183 (2018) 544-533.

Zhu, H., Yu, M., Zhu, J., Lu, H. and Cao, R. 2018. Simulation study on effect of permeable pavements on reducing flood risk of urban runoff. International Journal of Transportation Science and Technology (online): Available from https://www.sciencedirect.com (accessed: 03/04/2019).

APPENDIX A: LABORATORY EXPERIMENTAL DATA AND TYPICAL PERVIOUS INTERLOCKING PAVING BLOCK PAVEMENT PLAN

University of Johannesburg
Post Graduate Research: M Eng. Civil Engineering
Laboratory tests (Filtration tests)
Date: 19/09/2019
Type of water: Clean Sample type: Interlocking pavers

Test No.	Time period (seconds)	Initial water level (mm)	Final water level (mm)	Drop level (mm)	Drop level (m)
1	200	60	278	218	0.218
2	200	60	278	218	0.218
3	200	60	275	215	0.215
4	200	60	277	217	0.217
5	200	60	277	217	0.217
6	200	60	277	217	0.217
7	200	60	276	216	0.216
8	200	60	276	216	0.216
9	200	60	277	217	0.217

Type of water: Clean sample type: Concrete

Test No.	Time period (seconds)	Initial water level (mm)	Final water level (mm)	Drop level (mm)	Drop level (m)
1	200	60	193	133	0.133
2	200	60	193	133	0.133
3	200	60	190	130	0.13
4	200	60	190	125	0.125
5	200	60	185	125	0.125
6	200	60	185	125	0.125
7	200	60	185	125	0.125
8	200	60	185	125	0.125
9	200	60	185	125	0.125

Type of water: Clean Sample type: Asphalt

Test No.	Time period (seconds)	Initial water level (mm)	Final water level (mm)	Drop level (mm)	Drop level (m)
1	200	60	284	224	0.224
2	200	60	284	224	0.224
3	200	60	290	230	0.23
4	200	60	290	230	0.23
5	200	60	290	230	0.23
6	200	60	290	230	0.23
7	200	60	290	230	0.23
8	200	60	290	230	0.23
9	200	60	290	230	0.23

University of Johannesburg
Post Graduate Research: M Eng. Civil Engineering
Laboratory tests (Filtration tests)
Date: 20/09/2019

Type of water: Clean Sample type: Interlocking pavers

Test No.	Time period (seconds)	Initial water level (mm)	Final water level (mm)	Drop level (mm)	Drop level (m)
1	200	60	276	216	0.216
2	200	60	276	216	0.216
3	200	60	276	216	0.216
4	200	60	275	215	0.215
5	200	60	276	216	0.216
6	200	60	276	216	0.216

Type of water: Clean sample type: Concrete

Test No.	Time period (seconds)	Initial water level (mm)	Final water level (mm)	Drop level (mm)	Drop level (m)
1	200	60	170	110	0.11
2	200	60	168	108	0.108
3	200	60	168	108	0.108
4	200	60	170	110	0.11
5	200	60	170	110	0.11
6	200	60	169	109	0.109

Type of water: Clean Sample type: Asphalt

Test No.	Time period (seconds)	Initial water level (mm)	Final water level (mm)	Drop level (mm)	Drop level (m)
1	200	60	290	230	0.23
2	200	60	290	230	0.23
3	200	60	290	230	0.23
4	200	60	290	230	0.23
5	200	60	290	230	0.23
6	200	60	290	230	0.23

University of Johannesburg
Post Graduate Research: M Eng. Civil Engineering
Laboratory tests (Clogging tests with 0.5mm sand)
Date: 23/09/2019

Type of water: Contaminate Sample type: Interlocking pavers

Test No.	Time period (seconds)	Initial water level (mm)	Final water level (mm)	Drop level (mm)	Drop level (m)
1	200	60	260	200	0.2
2	200	60	215	155	0.155
3	200	60	215	155	0.155
4	200	60	210	150	0.15
5	200	60	210	150	0.15
6	200	60	210	150	0.15

Type of water: Contaminate sample type: Concrete

Test No.	Time period (seconds)	Initial water level (mm)	Final water level (mm)	Drop level (mm)	Drop level (m)
1	200	60	160	100	0.1
2	200	60	145	85	0.085
3	200	60	142	83	0.083
4	200	60	142	82	0.082
5	200	60	140	80	0.08
6	200	60	140	80	0.08

Type of water: Contaminate Sample type: Asphalt

Test No.	Time period (seconds)	Initial water level (mm)	Final water level (mm)	Drop level (mm)	Drop level (m)
1	200	60	290	230	0.23
2	200	60	280	220	0.22
3	200	60	270	210	0.21
4	200	60	270	210	0.21
5	200	60	270	210	0.21
6	200	60	265	205	0.205

University of Johannesburg
Post Graduate Research: M Eng. Civil Engineering
Laboratory tests (Clogging tests with silt)
Date: 24/09/2019

Type of water: Contaminate Sample type: Interlocking pavers

Test No.	Time period (seconds)	Initial water level (mm)	Final water level (mm)	Drop level (mm)	Drop level (m)
1	200	60	240	180	0.18
2	200	60	240	180	0.18
3	200	60	235	175	0.175
4	200	60	230	170	0.17
5	200	60	190	130	0.13
6	200	60	186	125	0.125

Type of water: Contaminate sample type: Concrete

Test No.	Time period (seconds)	Initial water level (mm)	Final water level (mm)	Drop level (mm)	Drop level (m)
1	200	60	135	75	0.075
2	200	60	130	70	0.07
3	200	60	126	66	0.066
4	200	60	125	65	0.065
5	200	60	116	56	0.056
6	200	60	115	55	0.055

Type of water: Contaminate Sample type: Asphalt

Test No.	Time period (seconds)	Initial water level (mm)	Final water level (mm)	Drop level (mm)	Drop level (m)
1	200	60	280	220	0.22
2	200	60	260	200	0.2
3	200	60	260	200	0.2
4	200	60	253	193	0.193
5	200	60	250	190	0.19
6	200	60	250	190	0.19

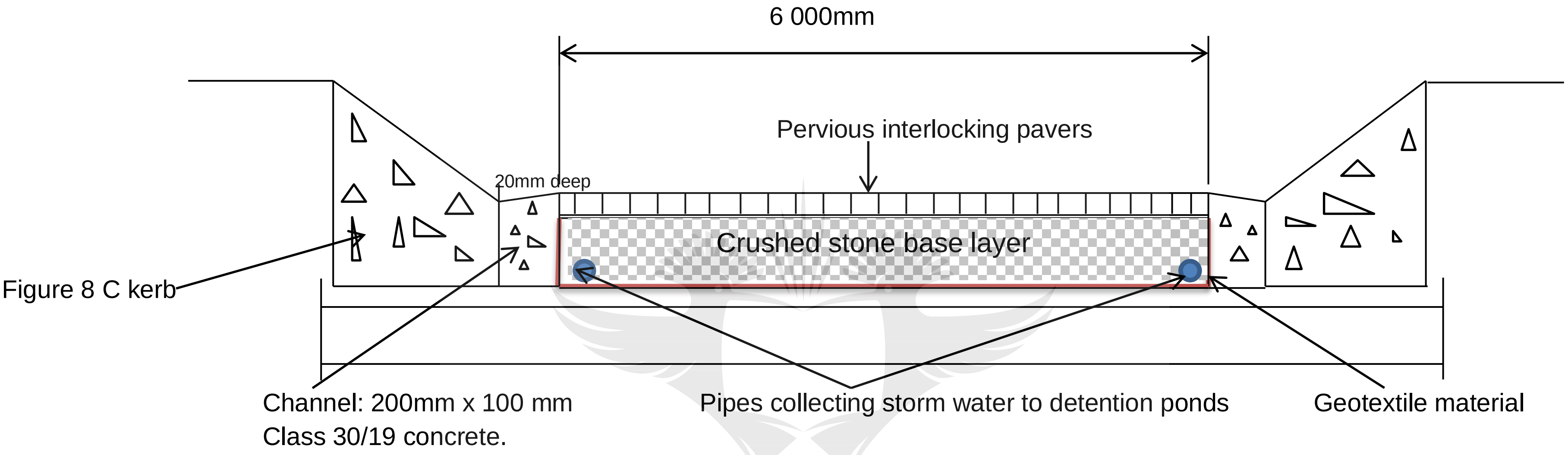

FIGURE A1a: Typical cross section of pervious interlocking paving blocks pavement

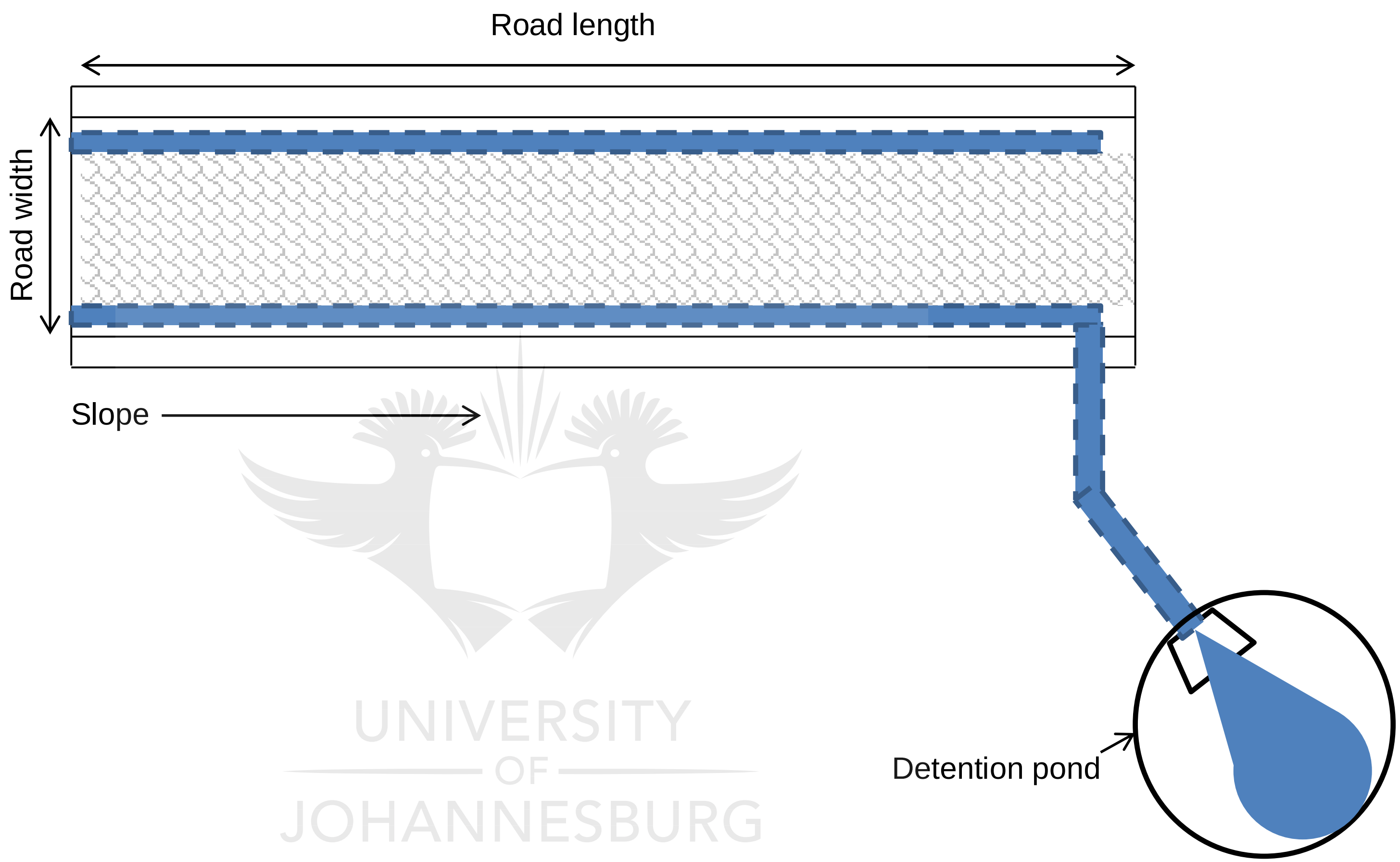

FIGURE A1b: Typical layout plan for pervious interlocking paving blocks pavement